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THE CONSTRUCTION OF THE PHILIPS AIR ENGINE

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621.412

A number of possible designs are discussed by which the hot-air process can be realised. The fundamentally simplest design of a single-cycle engine has two loaded pistons, while the hot and the cold spaces can be either both in one cylinder or in two separate cylinders (V-construction); the merits of these two types are compared. The old air engines had in general only one loaded piston and a transfer piston. The principle of that design is explained and two possible models are discussed; in one the cold space is divided between two cylinders, while in the other there is only one cylinder. It is on the latter principle that the Philips single-cycle air engine has been developed, with all the previously discussed improvements incorporated in it. A description is given of a number of structural details of this engine, which in efficiency and other properties is so much better than the old air engines as to be quite comparable with modern internal combustion engines, while in some respects it possesses a number of fundamental advantages. For higher powers the Philips multi-cylinder air engine has been developed, in which a number of hot-air cycles take place simultaneously. By a suitable combination of the systems necessary for the cycles, only one piston per system is needed (thus no separate transfer piston). This not only simplifies construction but also has the advantage that the direction of rotation can easily be reversed while the engine is running. Moreover, the pistons are double-acting, so that the driving mechanism is very lightly loaded. As a practical example a four-cylinder engine with a wobble-plate mechanism is illustrated, which is found to be very suitable for not too high powers (at most 20—30 h.p.) For higher ratings other types have been developed with a crankshaft mechanism. The mechanical solutions found for these different engines will be discussed in subsequent articles.

The theoretical principles of the air engine were discussed in the May 1946 number of this Review [1]). In a second article [2]), which we shall refer to as "II", further communications have recently been made about the knowledge gained from research carried out by Philips on the hot-air process. From this new insight into the process several new principles of construction have been derived which have made it possible to develop the Philips air engine with all its specific properties. We shall now describe various models of the engine in more detail. First we will deal with single-cycle engines, which may be compared with a single-cylinder internal combustion engine. In order to develop higher powers and to obtain balanced constructions, several single-cycle systems acting on a common shaft can be combined to form a multiple engine, as is the case with multi-cylinder internal combustion engines. (For certain reasons the term "multi-cylinder engine" will not yet be used for the multiple air engine.) In the development of the multiple air engine it has been possible to bring about a radical simplification and improvement allowing of very elegant designs.

Single-cycle engines

The principle

Fig. 1 is the single diagram that was also used in the previous articles to illustrate the practical realization of the hot-air process. The "hot space" V_w and the "cold space" V_k may be seen in open connection with each other *via* heater, regenerator and cooler. In the text underneath the diagram the four stages of the process are described: expansion of the working medium, cooling, compression and heating. The working medium is usually air, but it may also be hydrogen, helium, argon or some other gas. For a proper understanding of what follows it should be recalled that with sinusoidally moving pistons the four stages are not strictly separated but partially overlap, but that the machine continues to function as an engine with hardly any change in power and efficiency, provided the motions of the two pistons differ in phase by about 90°, in such a way that the volume variations in the hot space are in advance of those in the cold space. Furthermore, it must be pointed out that thanks to the open connections the momentary pressure is in principle the same everywhere in the engine: as the working medium is transferred from the cold to the hot space and *vice versa* so the pressure in the engine rises or falls as a whole.

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[1]) H. Rinia and F. K. du Pré, Air Engines, Philips Techn. Rev. **8**, 129-136, 1946.

[2]) H. de Brey, H. Rinia and F. L. van Weenen, Fundamentals for the development of the Philips Air Engine, Philips Techn. Rev. **9**, 97-109, 1947.

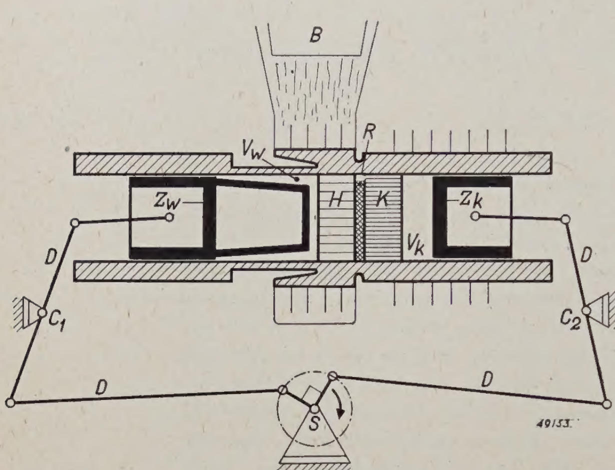

Fig. 1. Diagram of an air engine. The hot working medium (air for instance) in the hot space V_w expands, thereby performing work on the hot piston Z_w. It is then transferred, *via* the regenerator R where its heat is stored, to the cold space V_k and there compressed by the cold piston Z_k to its original volume. This requires work, but owing to the lower temperature and thus lower pressure the work thus expended is less than what is gained in the expansion, where the air is at a high temperature and thus under a high pressure. The air is then returned to the hot space *via* the regenerator, where it again takes up the heat stored there, and the cycle begins anew. The cooler K and the heater H, the latter heated by the burner B, ensure that the desired difference in temperature between the hot and cold spaces is maintained. The driving mechanism (connecting rods D, fixed pivots C_1, C_2, crankshaft S) is so constructed that the volumes V_w and V_k vary with about 90° phase difference.

Single-cycle model

It is possible to build an air engine exactly according to the scheme of fig. 1. It is even tempting to try it in this way, because theoretically, as far as the process in the cylinder itself is concerned, this is the most favourable form that can be imagined. In II it has been explained that in the construction of the heater, regenerator and cooler a compromise has to be made between the heat transmission on the one hand and the flow resistance and dead volume on the other, and that the right choice of this compromise is essential for high efficiency. In fig. 1 the situation is very favourable for the air flow: a short, straight connection with a large diameter between V_w and V_k; it is also possible to limit the dead volume to a minimum. For the purpose of our research, which in the beginning was directed mainly upon the points mentioned, this actually led us to build an engine to the design of fig. 1. A photograph of this experimental model is given in *fig. 2.*

The drawbacks depriving this design of any great practical importance are of a mechanical nature. The transmission is rather complicated. The housing of the driving mechanism, in a crankcase, as is customary in internal combustion engines for many obvious reasons (*i.a.* for good lubrication), involves elaborate and expensive constructions. Furthermore, the construction with the two pistons moving along the same line but with a certain phase difference cannot be balanced in a simple way — an objection which arises in the case of every normal single-cylinder engine and which weighs all the more in the designing of an engine with a high speed and or a high power. Finally, for the mechanical efficiency it is a great disadvantage that the construction outlined here works

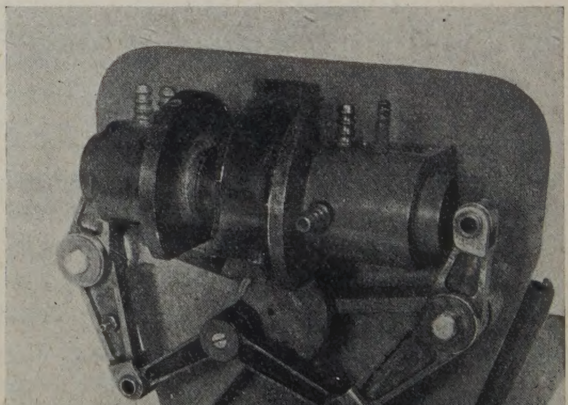

Fig. 2. Experimental model of an air engine constructed according to the principles of fig. 1. The position of the parts is the same as in fig. 1.

with two loaded pistons: there are different pressures on either side of each piston. In order to minimise leakage along the pistons, they have to fit tightly and this results in frictional losses. Owing to these losses it was hardly possible to apply the construction according to fig. 1 for the old air engines with their already very low efficiency. In nearly all the old models an entirely different design was used, with only one loaded piston; we shall return to this later. For our test model the situation was somewhat more favourable: various new ideas had already been incorporated in it, some of which have been discussed in II, and its efficiency was thereby so much improved that the engine did indeed work. But it offered little perspective, partly because of the objections already mentioned, but especially because of the two loaded pistons. The object of developing higher powers with a reasonably high efficiency and high specific power made it desirable to increase the pressure in the engine; this, however, involves still higher requirements as to the close fitting of the two pistons and thus still higher frictional losses result.

The V-construction

A number of the mechanical drawbacks mentioned in the foregoing are avoided by modifying the design of fig. 1 to that of *fig. 3*. The two halves of the cylinder in fig. 1 containing the hot and cold spaces have been turned into separate cylinders with their axes placed at an angle of 90° to each other. In this "V-construction" the driving mechanism is much simpler, a closed crankcase is possible and it is found that the engine can easily be almost completely balanced. If there is only one piston, by its motion to and fro transmitting to the driving mechanism an alternating force of acceleration parallel to the cylinder axis, that force can be wholly compensated with the aid of a counterweight rotating around the crank shaft [3]). This, however, introduces a new force, of equal magnitude and alternating at the same frequency, perpendicular to the original force; the centrifugal force of a rotating counterweight can be resolved into two perpendicular alternating forces with a mutual phase difference of 90°. This "compensation", therefore, really brings us little further. If, however, there are two identical pistons moving in a direction perpendicular to each other and with a phase difference of 90° — which is the case in our V-construction — then conversely the two alternating forces of inertia of the two pistons can be compounded to a single rotating force of constant magnitude. This resulting force on the crankshaft can therefore be wholly compensated by a counterweight acting in the opposite direction.

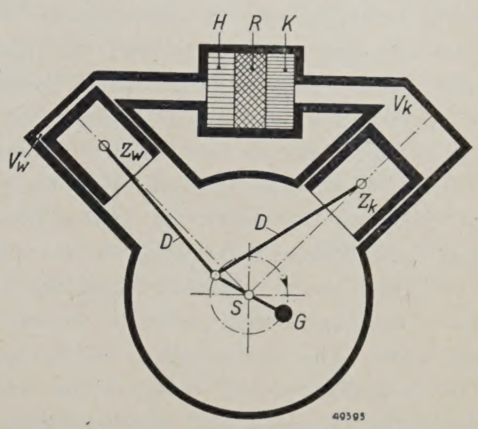

Fig. 3. Diagram of an air engine according to the so-called V-construction. The letters have the same meaning as in fig. 1. G = counterweight. Advantages: simpler drive, closed crankcase (possibly with elevated pressure), balanced inertia forces of the pistons.

The disadvantage of the two loaded pistons as mentioned in connection with fig. 1 also exists in the case of the V-construction, but here it does not count so much because in the case of an elevated pressure, where the frictional losses occur most, the crankcase can be put under pressure, thereby considerably reducing those losses. This method will be discussed in detail below in connection with another construction. Suffice it to say here that thanks to this and the other improvements described the V-construction is very suitable for high-speed engines of low power (for instance less than 1 h.p.) where the efficiency is not decisive.

Constructions with transfer piston

We have already mentioned that the old air engines nearly always had only one loaded piston. This was made possible by the use of a **transfer piston**: a body situated between the hot and the cold spaces and occupying (at least) as much volume as the maximum of the hot or cold space. By moving this body to and fro periodically the air is made to flow back and forth between the hot and cold spaces. The transfer piston is not loaded, because, as explained above, the pressure in the cold space is in principle the same at every moment as that in the hot space [4]. The cold space is shut off from the outside air by an ordinary piston. This single piston now serves both for the gain of work upon expansion and for the supply of work upon compression.

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[3]) Strictly speaking this holds only in the case of a driving mechanism with an infinitely long connecting rod. With a rod of finite length the piston does not move purely sinusoidally, its motion containing higher harmonics which, because of their higher frequency, can never be balanced by a weight rotating at the fundamental frequency.

Since there is no difference in pressure on either side of the transfer piston it is not necessary for that piston to be made to fit tightly in the cylinder, so that there need be no great frictional losses there. It is even possible — although, according to our present insight, not at all advisable — to leave channels open along or through the transfer piston for the free passage of the air in passing to and fro between the cold and hot spaces; we shall presently discuss a design used about 80 years ago when such was generally applied. But also in the designs where the hot and cold spaces have an "external" connection, the sealing of the transfer piston still only needs to satisfy moderate requirements, so that again there need not be any high frictional losses. This advantage is all the greater when the transfer piston drive is of such a construction as to avoid any appreciable lateral forces acting upon the transfer piston.

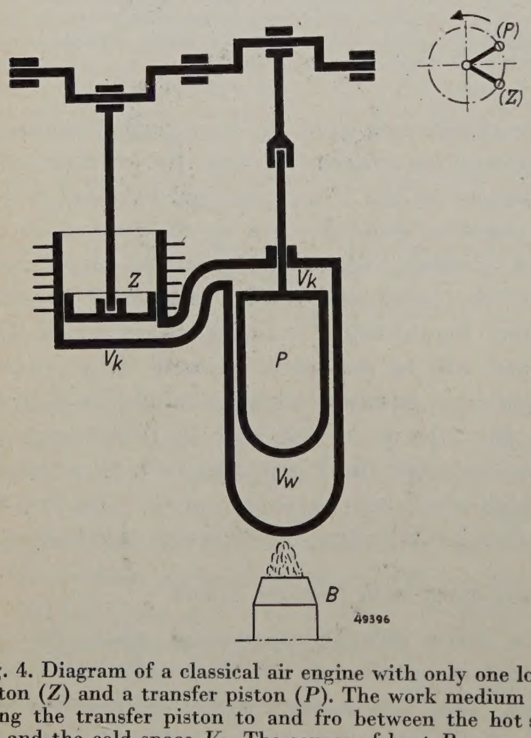

Fig. 4. Diagram of a classical air engine with only one loaded piston (Z) and a transfer piston (P). The work medium flows along the transfer piston to and fro between the hot space V_w and the cold space V_k. The source of heat B corresponds to the burner in fig. 1.

The principle of an air engine with transfer piston can be practically realized in various ways. An arrangement which was formerly commonly employed is represented diagrammatically in *fig. 4*. It was employed by Stirling as early as 1816. But the same type is still seen in the small air engines built at the present day and sometimes used as prime mover for stirring machines in chemical laboratories, as toys, etc.

In article II it has already been made quite clear why these old engines had such unsatisfactory properties as to cause them to lose the contest with internal combustion engines. We shall mention here only a few of the defects dealt with in that article. The heater and the cooler were very primitive (*cf.* fig. 4). Heating was done by means of a fire placed under the hot space, the walls of which were unable to withstand a very high temperature. Cooling took place by heat exchange with a cooling-water jacket *via* the wall of the cold space. In many of the old constructions there was no regenerator; thus, for instance, in the design of fig. 4, the work medium has to flow past the transfer piston to get from the hot space to the cold space and *vice versa*. Only the cylinder wall opposite the transfer piston plays, very ineffectively, the role of regenerator: the air coming from the cold space gets back at least part of the heat it gave off to the wall half a cycle earlier when coming from the hot space.

It would have been possible to apply the new ideas resulting from our investigations to the design of fig. 4. This was not done because of a fundamental drawback pertaining to that design: the cold space is divided between two cylinders. Since the piston and the transfer piston can certainly not move with a phase difference of 180° — the volume variations in the hot and cold spaces would then differ 180° in phase [5]) and the engine would not function — the volumes of the two parts of the cold space are never both zero at the same time. The smallest value of the cold volume thus being larger than zero, a high specific power can never be reached.

A better arrangement of an engine with transfer piston is shown in *fig. 5*. Here the cold space is not divided between two cylinders and by a suitable choice of the lengths of the stroke and the mutual phase difference between working piston and transfer piston both the hot and the cold volumes can be made equal to zero once per revolution [6]).

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[4] Actually there is a small difference in pressure due to the flow losses. There is also a slight difference in the areas upon which the forces act on either side of the transfer piston: at the side where the connecting rod is affixed to the transfer piston the rod cross-section has to be subtracted from the area. However, the remaining force in the connecting rod is very small. There is, therefore, practically no loss (nor gain) of work accompanying the motion of the transfer piston.

[5] Except at 180° the phase difference between the volume variations of the hot and cold spaces is always larger than the phase difference between the working piston and transfer piston movements. At the angle chosen in fig. 4 between the cranks the latter phase difference is 60°, the former 120°.

The conclusion to be drawn from the above is that the design given in fig. 5 must be considered to offer the best possibilities. In the Philips laboratories most of the experiments were in fact carried out on this type of engine, and these have led to the building of a model incorporating all the fundamental improvements described in II and several other incidental improvements. It is this new engine that will now be described.

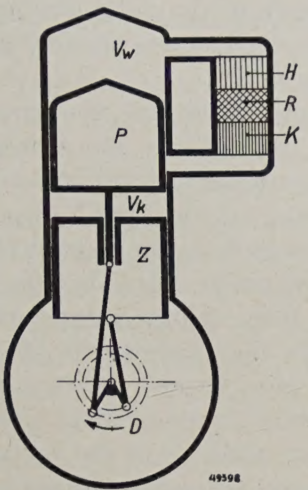

Fig. 5. Diagram of an air engine with transfer piston where only one cylinder is used. For the meaning of the letters see figs. 4 and 1.

The single-cycle Philips air engine

We will first give a brief summary of the new principles of construction discussed in II which have been applied in this engine: transition to high pressures and to a high temperature of the hot space, made possible by the employment of heat and creep-resisting steel alloys; effective construction of the heater, cooler and regenerator, so that a sufficiently rapid heat transfer is obtained without involving too great dead volume and flow resistance (at the high speeds of the Philips engines); reduction of chimney losses by the introduction of an efficient heater; general limitation of heat losses by small compact design; general reduction of frictional losses by small compact build.

The most important details of the engine are to be seen in *fig. 6*. The heater, regenerator and cooler, instead of being placed in a separate communication channel between the hot and cold spaces, as may seem the obvious way and as is indicated in fig. 5, are given an annular shape and placed around the cylinder. This produces a very compact arrangement, while at the same time, with the absence of inlet channels, unnecessary flow resistance and dead volume are avoided. The heater, which is enclosed on the inside by a thin-walled cylinder of heat-resisting metal, opens directly into the hot space. The heater is heated externally by means of a burner. The cold space is in communication with the cooler *via* a ring of ports in its wall. For further details of the construction of the heater, cooler and regenerator see II.

The lower part of the transfer piston is provided with a bearing surface while the upper part in the hot space consists of a thin-walled cap leaving some clearance in the cylinder (see fig. 6). This cap, which is made of heat-resisting material with low heat conductivity (nickel-chromium steel), fulfils an important function. This thin, poorly conductive wall of the cap ensures that only very little heat flows through it from the hot top end to the cold bottom end. Furthermore, there is only a minimum transfer of heat through the thin layer of gas in the annular space between the cap and the

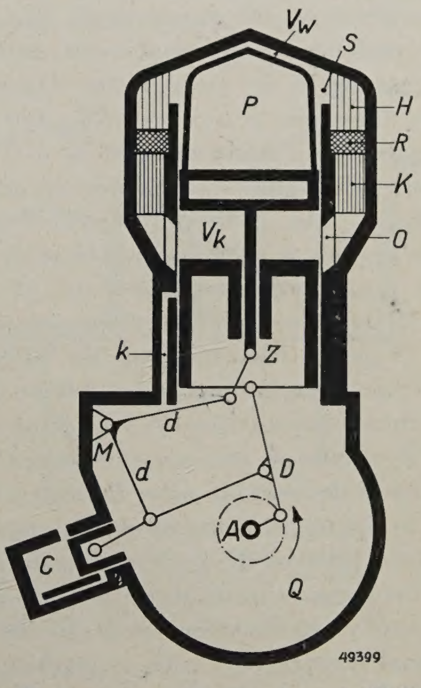

Fig. 6. Cross section of the single-cycle Philips air engine. The hot and cold spaces, respectively V_w and V_k, are in one cylinder and separated by transfer piston P with insulating cap. The heater H, regenerator R and cooler K are annular in shape and built around the cylinder. S outlet of heater into V_w, O ports between cooler and V_k. The connecting rod D of the piston Z and the driving mechanism d of the transfer piston are housed in a closed crankcase Q, in which air is maintained at the minimum pressure of the cycle in the cylinder. The drive d with fixed pivot M is such that only extremely small lateral forces act on the transfer piston. Air which has leaked into the crankcase is returned to the cylinder *via* the channel k. C pressure pump; A engine shaft.

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[6]) A design with work piston and transfer piston in one cylinder is fairly old; it was employed around 1860 by Lehmann.

cylinder wall. Thus any loss of heat that might in principle be due to the transfer piston is limited. Still more important, however, is the fact that thanks to this insulating action of the cap the bearing surface of the transfer piston is kept cold. This avoids all the difficulties of tight-sealing, wear, etc. which are encountered with hot sliding surfaces.

It is to be pointed out that it is thanks to the nature of the hot-air process that the cap construction described gives no difficulties. In internal combustion engines the material of such a cap would be too quickly destroyed by the very high temperatures of combustion. Especially in the case of petrol engines the hot cap would furthermore lead to premature combustion of the mixture of fuel and air. Moreover, the clearance between the cap and the cylinder wall would soon become clogged up by the deposition of carbon or other products of combustion, thus increasing friction and causing damage to the running surface of the piston.

The engine is provided with a closed crankcase. The air in the crankcase is kept at the desired pressure by means of a small pump (*C* in fig. 6) which pumps air from the outside into the crankcase and is driven by the engine itself. The pressure in the crankcase is kept equal to the minimum pressure occurring in the cycle of the engine. If, for instance, the engine is to work with a top pressure of 20 atm. and a minimum pressure of 8 atm. the crankcase is brought to 8 atm. This has important advantages. The greatest differential pressure at the piston is thereby considerably restricted (in the example mentioned to 12 atm; while with a crankcase at atmospheric pressure it would be 19 atm.), leakage along the piston is reduced, piston sealing is simplified and there is less friction. With this construction the air leaking along the piston at maximum pressure is returned from the crankcase to the working space through a small channel (*k* in fig. 6) momentarily making an open communication between the work space and crankcase when the piston is in its lowest position (state of approximately minimum pressure). In the case of the normal construction with a crankcase at atmospheric pressure the air to be returned would first have to be compressed to the minimum pressure (here 8 atm.), but with this design the return of air requires much less work. Any leakage from the crankcase to the outside is now only possible along the engine shaft (*A* in fig. 6), and this is counteracted by applying the usual kind of shaft packing.

We have just stated that the pressure in the crankcase is made equal to the minimum pressure in the cycle. Actually it is just the reverse: through the open connection at the lowest position of the piston the minimum pressure of the cycle is automatically made equal to the crankcase pressure. Therefore, by adjusting the crankcase pressure with the help of the pump the pressure and thus the power of the engine can be regulated in a very simple way.

When the engine has not been used for a long time the pressure in the crankcase may have dropped to atmospheric pressure due to the possible slight leakage to the outside. Upon being started up again, therefore, the engine will at first develop only a low power, but this rises in a very short space of time as the pump quickly raises the pressure in the crankcase to the desired level.

Finally the elevated pressure in the crankcase offers another great advantage with respect to the mechanical efficiency of the engine. Owing to the fact that the alternating difference in pressure on either side of the piston is lowered by a constant amount, the forces of the piston rod that have to be transmitted to the crankshaft are reduced accordingly. There is thus a lighter load on the bearings

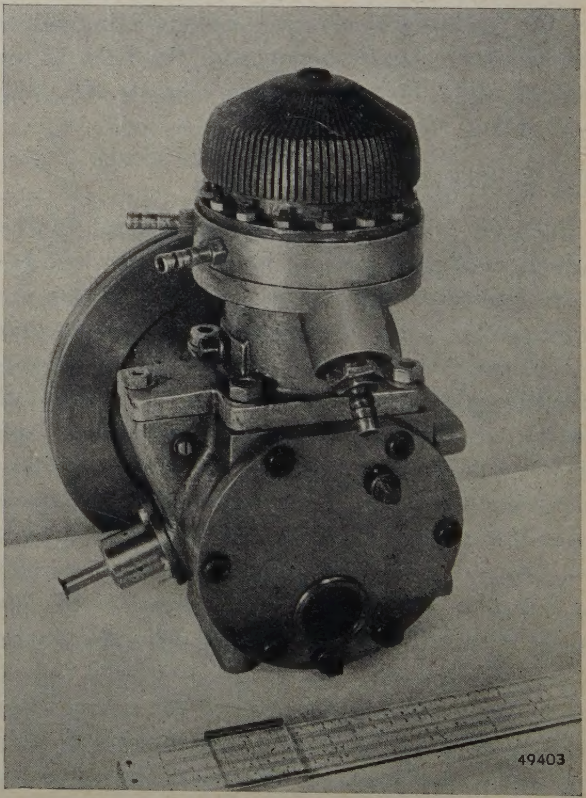

Fig. 7. Photograph of an experimental model of the single-cycle Philips air engine built according to the diagram of fig. 6. At the top is the heat exchanger of the burner, built around the heater (*cf.* article II). At the bottom on the left is the pump with screw for regulating the pressure. Behind the engine is the flywheel.

and the frictional losses are therefore less. A similar effect in a still more pronounced form will be found in the multiple engine.

A photograph of an engine of the type described is reproduced in *fig.* 7. With this model a large number of test measurements have been taken which will be dealt with in another article. We would only state here that the efficiency of this type of engine is now quite satisfactory, many times better than that of previous air engines. This type is suitable for a rating of several h.p. and not too high speeds (*e.g.* up to 2000 r.p.m.). The limited speed is due to the fact that, just as in the case of the primitive model in fig. 2 and in all kinds of single-cylinder engines, the engine cannot be balanced in a simple manner. The need for a proper balancing and higher powers brings us to the multiple engines.

Multiple engines

Although the results obtained with the single-cycle engines were already very satisfactory, further development was greatly stimulated when it was found that in multiple or multi-cylinder engines the construction could be greatly simplified.

We must pause a moment to consider the term "multi-cylinder engine". In the foregoing we have seen that some types of single-cycle engines have two cylinders (figs. 3 and 4), while others have only one cylinder (figs. 1, 5, 6). All these engines we could call single-cycle engines, because they possess only one "system" consisting of cold space, cooler, regenerator, heater, hot space. In the case of the multiple Philips air engines about to be described, however, the number of cylinders is in every case equal to the number of systems, so that for instance the term "four-cylinder engine" can no longer cause any misunderstanding.

The simplification in construction mentioned above lies in the manner in which several systems are combined to form a multiple engine. In *fig. 8* the principle is illustrated for the case of a four-cylinder engine. In each of the four cylinders there is a hot space (above) and a cold space (below). Contrary to what might be expected, however, the hot and cold spaces in each cylinder do not form a coordinated system, for here the hot space of one cylinder is connected — *via* a heater, regenerator and cooler — with the cold space of the next cylinder [7]). Such an arrangement could be compared, for instance, to that of fig. 3, for in both cases it is immediately to be seen that upon expansion of the working medium the two pistons between which the system is situated will deliver more work to the engine shaft than what they have to perform for compression of the working medium within the system, provided the volume variations of the hot space (in the first cylinder) are advanced in phase with respect to the variations in the cold space (in the second cylinder) according to the conditions already given. It is easy to see that this is ensured when the piston of the second cylinder is in advance of that of the first — a condition that can be satisfied in a very natural way, since in a multi-cylinder engine the series of pistons will never be made to move in phase.

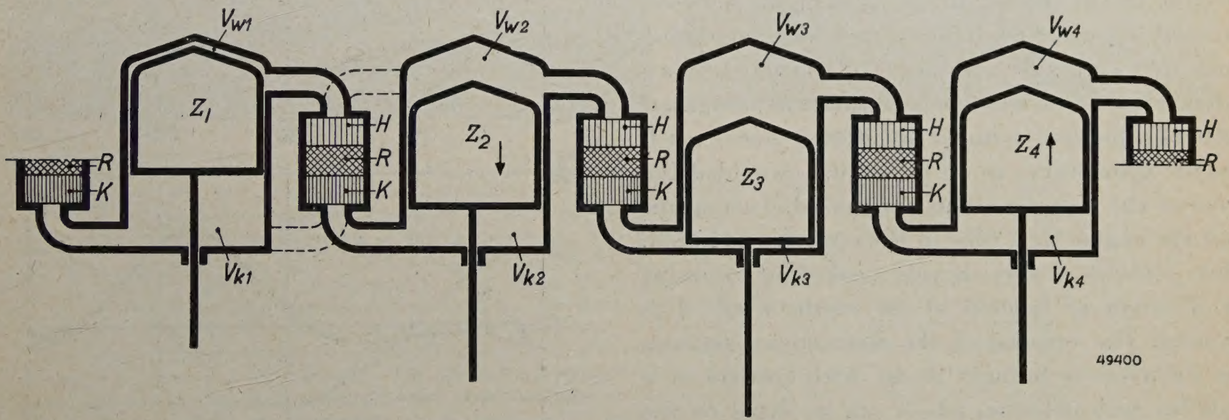

Fig. 8. Principle of the Philips multi-cylinder air engine. In each of the four cylinders is a hot space at the top, V_{w1} to V_{w4}, and a cold space at the bottom V_{k1} to V_{k4}. The hot space of each cylinder is connected *via* a heater *H*, regenerator *R* and cooler *K*, with the cold space of the next cylinder. The pistons Z_1-Z_4 of the successive cylinders move with a suitably chosen phase difference (in the case shown with four cylinders this is 90°).

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[7]) This principle has already been described by H. Rinia in his article: New possibilities for the air engine, Proc. Kon. Ned. Akad. Wet., Amsterdam, **49**, 150-155, Febr. 1946.

What has been stated here for one pair of pistons and the system between them also holds for the rest. If, therefore, each of the four pistons in fig. 8 is made to move in advance of the preceding one, each of the four systems works as an air engine. *With this simple combination of the systems the transfer pistons with their driving mechanism are dispensed with.* Needless to say, this means a very important mechanical simplification and allows of a considerable increase in mechanical efficiency.

As to the phase differences of the pistons, it is obvious that with four pistons there should be a phase shift of 90° in their motions. The volume variations of corresponding hot and cold spaces then likewise differ 90° in phase. Combinations can also be made with more than four systems, of course with different phase differences. Within certain limits this has little effect upon the efficiency of the engine, since the curve representing the efficiency of the hot-air process as a function of the phase difference between the hot and cold spaces is fairly flat in the neighbourhood of the maximum.

With the method of communication between the hot and cold spaces as shown in fig. 8 each piston must be in advance of the preceding one. This order of piston movements determines the direction of rotation of the engine. If the connections between the cylinders are interchanged, each hot space being connected with the cold space of the preceding cylinder (in fig. 8 this has been indicated diagrammatically for one cylinder by dotted lines), each system again works as an air engine, provided the order of the piston motions is reversed. This means that the engine then runs in the opposite direction. *This provides a very simple method of reversing the direction of rotation of the engine while it is running.* The reversal of the connections between the cylinders is brought about with the aid of a slide for each cylinder, which can be fitted on the cold side of the engine (see below).

It is also of importance that in a multi-cylinder engine each piston is double-acting. To understand this properly let us first consider fig. 6. There, as in all the engines so far dealt with, the piston is single-acting, because it transmits energy from the work medium to the crankshaft only during the down stroke, while on the up stroke work is performed on the working medium. The first-mentioned work is larger than the latter, the difference being the mechanical energy gain. But the frictional losses bear a definite relation to the total energy conversion in the driving mechanism, no matter whether the various energy contributions count in a positive or a negative sense for the consumer. By way of contrast now let us turn to fig. 8: there each piston transmits energy from the working medium to the engine shaft both on its down stroke and on its up stroke, for each piston is situated between two systems which, for convenience, we shall call the left-hand and the right-hand systems. The upward stroke of the piston coincides for a large part with the expansion of the left-hand system and with the compression of the right-hand system; conversely the down stroke is for the greater part simultaneous with the expansion of the right-hand and the compression of the left hand system. In both cases, therefore, the compression in one system is brought about for a large part directly by the expanding medium in the neighbouring system, only *via* the body of the piston; the driving mechanism takes no part in this, only transmitting the excess of work furnished by each expansion. The energy conversion in the driving mechanism

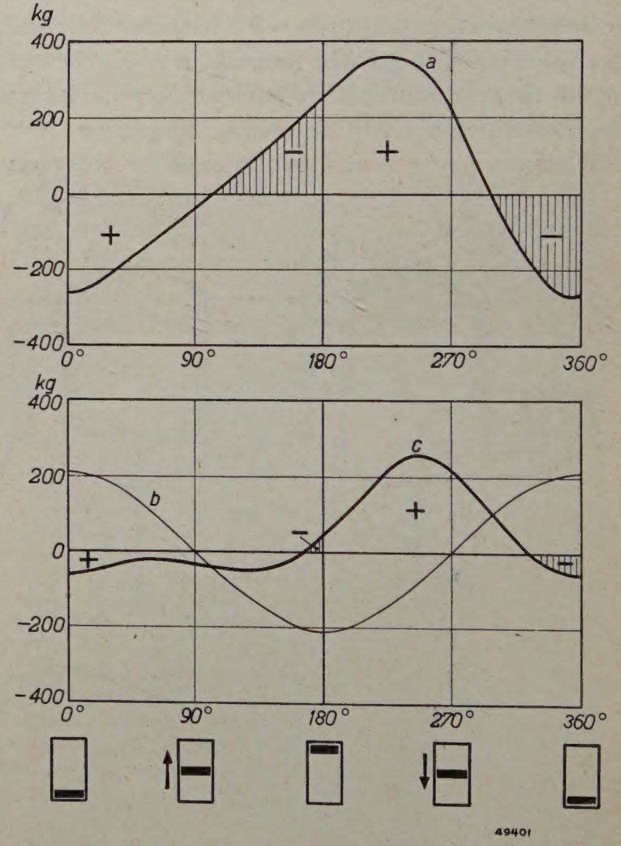
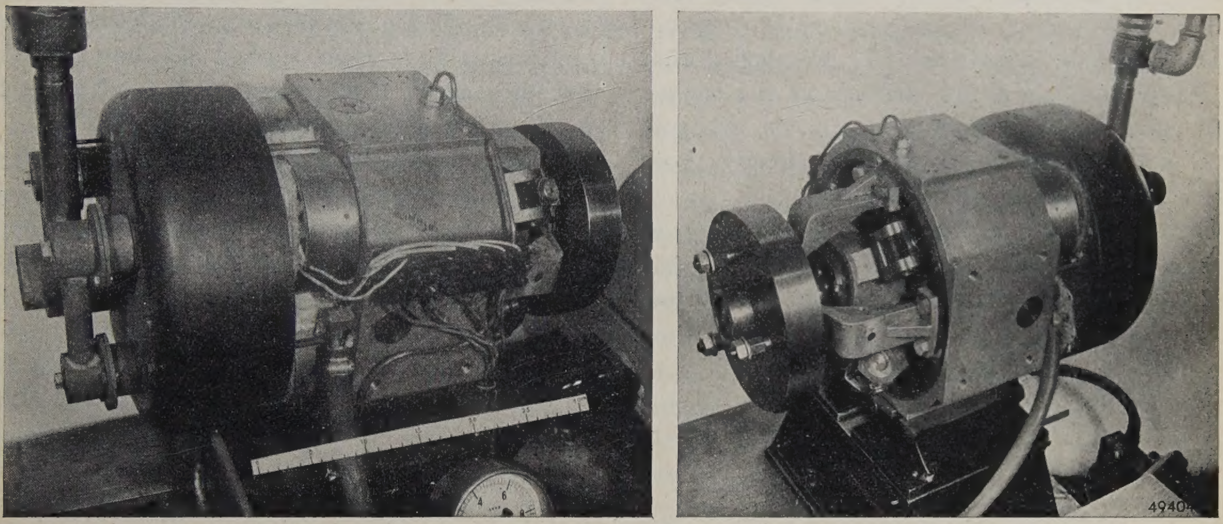


Fig. 9. Diagram for the forces in the connecting rods for a given 20 h.p. four-cylinder air engine with a speed of 3000 r.p.m. at full load. The force (in kg) of the connecting rod of a cylinder is plotted as a function of the crankshaft angle. The left-hand half (0-180°) corresponds to the up stroke, the right-hand half to the down stroke. Forces directed downward are reckoned to be positive; + and — indicate that during the intervals in question the piston delivers positive or negative work to the crankshaft. Curve *a* = gas force, *b* = inertia force, *c* = resulting force in the connecting rod. The curve *c* shows that in this four-cylinder engine each piston is practically purely double-acting.

is therefore no greater than what corresponds to the power of the engine, and consequently the frictional losses are also limited.

This rough picture needs correcting on two points. In the first place there is the fact that for each piston in fig. 8 the expansion of the left-hand and the compression of the right-hand system coincide only "for the greater part" with the up stroke (and *vice versa*). Secondly, in the energy conversion in the driving mechanism we have still to take into account a "wattless component", *viz.* the inertia forces of the moving masses of piston, connecting rod, etc. In regard to these forces we will consider the diagram in *fig. 9* for the forces in the connecting rods. Curve *a* gives the variation of the "gas force", *i.e.* the force exerted by the working medium (of the two adjacent systems together) on each connecting rod, as a function of the crankshaft angle, for a given four-cylinder engine. A force directed downwards is here plotted positive; the abscissa 0° corresponds to the lowest position of the piston; the left-hand half of the diagram thus corresponds to the up stroke and a positive gas force here performs negative work on the engine shaft, whilst a negative force yields positive work. In the right-hand half this is reversed. It is in this sense that the plus and minus signs in the diagram, referring to the work performed on the shaft, are to be understood. It may be seen that the gas forces do indeed require work of the connecting rod during two intervals of time per revolution. It is found, however, that it so happens that the greater part of this work can be supplied by the inertia forces; see curve *b* and the resulting rod force curve *c* in fig. 9. Of course no energy is thereby gained, because the inertia forces consume a corresponding amount of energy again in the rest of the period. But, as curve *c* shows, the piston has now practically become purely double-acting, so that our original conclusion remains valid.



a *b*

Fig. 10. Photographs of a practical model of the Philips multi-cylinder air engine: four-cylinder engine with parallel cylinders placed in a square with a wobble-plate mechanism for the transmission of the motion of the four pistons to the engine shaft. The engine can deliver 15 h.p. at 3000 r.p.m. The model shown is run with gas as fuel.

a) In this photograph the hot side of the engine is on the left and the cold side on the right. The pipe for the fuel supply is on the extreme left. The cap on the left contains the heater. Part of the jacket of three cylinders is visible. On the extreme right are the wobble-plate mechanism and the flywheel. With this mechanism the engine shaft is parallel to the axes of the cylinders. The driving mechanism is in a closed crankcase, the cover of which has been removed here for clearness. The wires connected to the terminal board in the middle are connections to a number of thermo-elements introduced at various points in the engine for taking test measurements. (The scale is drawn in centimetres.)

b) The same engine seen from the other side. It gives a better view of the wobble-plate mechanism between the flywheel and the engine block. Note the compact construction obtained with this mechanism.

Owing to the relatively small forces in the connecting rods the multi-cylinder air engine compares favourably with an internal combustion engine of the same power per cylinder, the same swept volume and the same speed. In fig. 9, which relates to an air engine of 5 h.p. per cylinder and a speed of 3000 r.p.m., the peak value of the resulting force in the connecting rod is about 250 kg. In a comparable internal combustion engine, on the other hand, there is a maximum force in the connecting rod of about 1200 kg. These smaller connecting rod forces in the air engine mean less load on the bearings, a factor of great importance for the construction.

As to the practical construction of the multi-cylinder engine, it has been possible to apply practically unaltered many of the structural elements described in connection with the single-cylinder engine, such as the annular-shaped heater, regenerator and cooler around each cylinder, the insulation caps on the pistons serving to keep the running surfaces cool, etc. A new problem, however, was how to arrange the position of the various cylinders and the transmission of all the piston forces to one shaft. In this article we can only briefly touch upon these points.

The cylinders will preferably be arranged so that all the cold spaces lie on one side of the engine, with all the driving mechanism, etc. on this cold side. Such an arrangement has already been assumed in the diagram of fig. 8.

In that diagram the four cylinders are in a row. This arrangement has the objection that a long connecting channel is necessary between the last and the first cylinder, which involves losses. In order to avoid this the four cylinders can be placed in star formation, as is customary in aircraft engines (the cold side is then in the centre of the star), or in two V's one behind the other, as is done in some automobile engines. Another possibility is to place the four cylinders parallel to each other and bundling there as it were) in a square. Whereas with the first two arrangements a crankshaft construction can be used for converting the linear motion of the pistons into the rotating motion of the engine shaft, in the last case mentioned a wobble-plate mechanism is indicated. The practical model of the Philips multi-cylinder air engine illustrated in *fig. 10* is constructed in the last manner, but this design is considered only suitable for air engines of some 20—30 h.p. For higher powers other driving mechanisms have been worked out, based on the abovementioned arrangement of the cylinders in two V's one behind the other.

It would lead us beyond the scope of this present article to go deeper into the mainly mechanical details of these different designs and the reasons for their choice. These will be left to be dealt with in further articles in this periodical.

VOLTAGE IMPULSES IN RECTIFIERS

by Tj. DOUMA.

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The valves in a rectifier may be regarded as switches opening or closing electric circuits at certain moments. This is accompanied, as a rule, by transient phenomena, which manifest themselves, *inter alia*, in voltage impulses on self-inductances occurring in the circuits; when valves with a variable ignition moment are employed these impulses or peaks are exceptionally high in cases where the rectified voltage has been stepped down more or less by delaying the moment of ignition. Owing to the presence of parasitic capacities, oscillating circuits are formed and, moreover, the voltage peaks are concentrated on the outermost windings of the transformer and any other coils. In rectifiers for high tensions, such as for high power transmitters, this is apt to endanger the insulation. Various methods are indicated for avoiding this danger, such as the introduction of anode choke coils and of condensers with damping resistances.

Introduction

When a sudden change takes place in an electrical system carrying currents — for instance through the short-circuiting or opening of a branch of the network — in course of time a stationary condition of the currents and voltages will set in which in general differs from the condition that prevailed immediately before the change took place. The difference existing between this ultimate condition and the actual condition as from the moment of switching is called the transient phenomenon. Owing to the dissipation of energy it gradually dies out and thus forms a bridge between the old state and the new state.

Such transient phenomena are brought about not only by switching operations, for in rectifiers, for example, they continually occur during normal working. This will be readily understood when it is considered that a relay valve bears a great resemblance to a switch: so long as the anode is negative with respect to the cathode the relay does not allow any current to pass (or at least only a negligible current), so that it corresponds to an open switch; when the relay allows a current to pass through (in the right direction) this is accompanied by a voltage drop which, though greater than that with a normal switch, is generally small compared with the working voltage, so that in this case the relay acts as a closed switch. While a rectifier is working its relays "open" and "shut" at certain moments, each time giving rise to a transient phenomenon. Not only do these transient phenomena partly govern the moments when the relays become dead (thereby influencing the general picture of the working of the rectifier), but at those moments in certain cases voltage impulses arise with a steep front and large amplitude, which impulses may seriously endanger the insulation of the transformer or choke coils forming part of the rectifier. Such phenomena occur especially when the moment (recurring for each cycle of the mains frequency) at which the relays begin to pass through current — the so-called ignition moment — has been artificially delayed with respect to the earliest possible ignition moment in order to reduce the rectifier voltage. This may be done by using relay valves, *e.g.* rectifying valves, with gas filling and control grids, to which latter an alternating voltage is applied which in phase is behind the anode alternating voltage, or else by employing mercury cathode valves with, *e.g.*, a capacitive starter, to which ignition impulses are applied at the desired moments [1]).

In rectifiers one has to do not only with the regularly recurring transient phenomena just mentioned, resulting from the periodical opening and shutting of the valves, but also with the transient phenomena caused by the "ordinary" switching operations. These latter phenomena will be left out of consideration here.

The voltage impulses referred to above are excited in the self-inductance of the rectifier. In the rectifiers with which we are mainly concerned here — those for supplying the anode voltage of transmitters — there is generally a self-inductance in two places, *viz.* in the choke coil — which serves to reduce the ripple of the rectified current — and the leakage inductance of the transformer coils, *i.e.* the inductance corresponding to the magnetic lines of force in the transformer that are connected only with a primary or a secondary coil (or a part of these coils).

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[1]) A rectifier provided with relay valves having a filament cathode and a control grid was described in Philips Techn. Review **1**, 161-165, 1936. An article on the action of relay valves with a mercury cathode and a capacitive igniter has been published in Philips Techn. Rev. **9**, 105-113, 1947.

However, also the capacities of the windings are of great importance, in two respects: 1) they govern, at least at the moment that the voltage impulse arises, the distribution of the impulse between the windings connected in series; 2) in combination with the above-mentioned inductances they form oscillating circuits which are activated by the transient phenomenon.

These voltage impulses will now be examined and means will be indicated for counteracting them successfully. We will start by considering a simple rectifying circuit working on only one phase of the alternating voltage, after which we will proceed to discuss the more common circuits with several phases, each case being treated first without consideration of the influence of the capacities and then by taking this influence into account.

Rectifier working on one phase of the alternating voltage

In the simple circuit of *fig. 1* the leakage inductance is represented by the separate inductance L_a in series with the secondary circuit, which also comprises the secondary transformer coil in which at no load the alternating voltage $v = V_{\max} \sin \omega t$ is induced, the valve *Re* (with gas filling and a control grid, thus a relay valve), a choke coil with the self-inductance L_0, a resistance r and the parallel circuiting of the load resistance R and the condenser C_0. The object of this condenser is to reduce the voltage ripple on the terminals of R; so as not to make the matter unnecessarily complicated we will assume that this ripple is negligible.

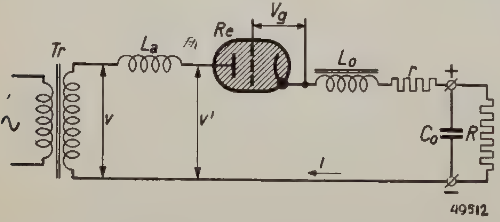

Fig. 1. Rectifying circuit fed by a monophase alternating voltage. Given a sufficiently large capacitor C_0, the ripple of the voltage V_0' on the load resistance R may be ignored. Re = relay valve, the ignition moment of which is regulated by the phase of the grid alternating voltage v_g; L_0 = self-inductance of the choke coil; L_a = leakage inductance of the transformer; $v = V_{\max} \sin \omega t$ is the secondary voltage under no load; v' = terminal voltage; r = resistance of the choke coil and the transformer.

The amplitude of a relatively small ripple voltage is about p% or less ($p \ll 100$) of the direct voltage when C_0 and R satisfy the equation

$$\omega C_0 R \geqq 100\ \pi/p.$$

In the case of the rectifiers with m phases to be dealt with later this condition is:

$$\omega C_0 R \geqq 100\ \pi/mp.$$

A pulsating current i will flow through the circuit. The current impulse starts at a moment t_0 which can be fixed between certain limits, for instance by regulating the phase of the grid voltage v_g; this impulse ends at a moment t_d, which will be further defined presently. At these two moments the current curve makes a bend and consequently the voltage at the self-inductances L_a and L_0 will undergo a sudden change of the order of $L_a \mathrm{d}i/\mathrm{d}t$ and $L_0 \mathrm{d}i/\mathrm{d}t$ respectively, where $\mathrm{d}i/\mathrm{d}t$ applies for the moments $t = t_0$ and $t = t_d$. In order to calculate these voltage jumps we have to consider the differential equation of the circuit:

$$L_a \frac{\mathrm{d}i}{\mathrm{d}t} + v_{\mathrm{arc}} + L_0 \frac{\mathrm{d}i}{\mathrm{d}t} + ri + V_0' = v = V_{\max} \sin \omega t.$$

where V_0' is the condenser voltage assumed to be constant and v_{arc} the momentary value of the arc voltage of the relay valve. By a good approximation this may be taken to be independent of the current, so that it may be regarded as a rectified voltage. If we combine this and the condenser voltage to form together one direct voltage $V_0 = v_{\mathrm{arc}} + V_0'$ and add the two self-inductances to make one self-inductance $L = L_a + L_0$, and further by substituting τ for ωt, then the equation may be written as:

$$\omega L \frac{\mathrm{d}i}{\mathrm{d}\tau} + ri = V_{\max} \sin \tau - V_0. \quad . \quad . \quad (1)$$

At the moment t_0 at which the current begins to flow — owing to the grid voltage of the relay valve then exceeding the critical value — we have the "ignition angle" $\omega t_0 = \tau_0$. The terminal voltage v' of the secondary transformer coil has at that moment the value

$$(v')_{t_0} = V_{\max} \sin \tau_0 - (L_a \frac{\mathrm{d}i}{\mathrm{d}t})_{t_0} =$$

$$= V_{\max} \sin \tau_0 - \frac{L_a}{L} (\omega L \frac{\mathrm{d}i}{\mathrm{d}\tau})_{\tau_0}.$$

At the moment of ignition there is thus a jump in the terminal voltage of the order of

$$(\Delta v)_0 = \frac{L_a}{L} (\omega L \frac{\mathrm{d}i}{\mathrm{d}\tau})_{\tau_0}.$$

Substituting the value of $\omega L\, \mathrm{d}i/\mathrm{d}\tau$ from (1) and bearing in mind that at the moment $t = t_0$ the current $i = 0$, then we find:

$$(\Delta v)_0 = \frac{L_a}{L} (\sin \tau_0 - \frac{V_0}{V_{\max}}) \cdot V_{\max} =$$

$$= \frac{L_a}{L_0 + L_a} \cdot (\sin \tau_0 - q) \cdot V_{\max}, \quad . \quad . \quad (2)$$

where q represents the voltage ratio $V_0/V_{\max}$. The jump is clearly seen in *fig. 2* giving the oscillogram of the secondary transformer voltage in a still further simplified circuit.

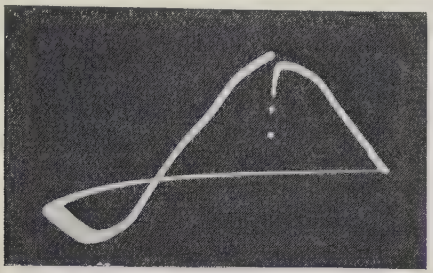

Fig. 2. Oscillogram of the secondary terminal voltage v' in a rectifier on the principle of fig. 1 with $L_0 = 0$, $C_0 = 0$, ignition angle τ_0 = appr. 90°. Upon ignition a voltage impulse arises in the leakage inductance L_a.

Another bend occurs in the current curve when i is zero, thus when the valve is extinguished ($t = t_d$, to which corresponds $\omega t_d = \tau_d$ = the "extinction angle"). We then find for the jump in the terminal voltage:

$$(\Delta v)_d = \frac{L_a}{L_0 + L_a} \cdot (\sin \tau_d - q) \cdot V_{\max}. \quad . \quad (3)$$

The fact that nothing is seen of this jump in fig. 2 is due to the fact that this oscillogram was recorded under circumstances where $q = 0, \tau_d \approx 180°$, so that $(\Delta v)_d$ was very small.

Similar jumps occur for the self-inductance L_0 and these can be expressed by substituting L_0 for L_a in the numerator of equations (2) and (3).

As to the size of these jumps, from equations (2) and (3) one sees in the first place that the two self-inductances L_a and L_0 function as voltage dividers and further that for a given peak value $V_{\max}$ of the alternating voltage the jumps are the greatest when q is as small as possible, thus when the condenser voltage is zero (which is the case with short-circuiting, $R = 0$). Moreover, there is a big jump upon ignition when this takes place at the moment at which the alternating voltage reaches its peak value ($\sin \tau_0 = 1$).

To investigate this more accurately we have to consider more closely the quantities q and τ_d, occurring in (2) and (3), which in general are functions of τ_0, R, r, L and ω. Here the resistance r, which in practical cases consists only of the resistance of the transformer, of the choke coil and of the conductors, is usually of little significance. Ignoring this resistance, it appears that τ_d and q may be written as the functions of two variable quantities τ_0 and φ, the latter being defined by $\operatorname{tg} \varphi = \omega L/R$. Briefly this calculation is arrived at in the following way:

For $r = 0$ equation (1) becomes

$$\frac{di}{d\tau} = \frac{V_{\max}}{\omega L} (\sin \tau - q), \quad . \quad . \quad . \quad . \quad (4)$$

to which correspond the limiting conditions

$$i = 0 \text{ for } \tau = \tau_o \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and

$$i = 0 \text{ for } \tau = \tau_d \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Equation (4) is easily integrated and the integrating constant can be determined with the aid of (5). With the aid of (6) we then find a relation between τ_0, τ_d and q. A second equation of these quantities follows from the condition that per cycle the charging of condenser C_0 equals its discharge. These charges amount to

$$\int_{t_o}^{t_d} i \, dt \text{ and respectively, } \frac{V_0'}{R} T,$$

where T is the duration of a cycle. Thus

$$\int_{\tau_o}^{\tau_d} i \, d\tau = 2\pi \frac{V_0'}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

By substituting in this equation the expression found from (4) and (5) for i, then we get a second relation between τ_0, τ_d and q, from which, in combination with that already found, τ_d and q can be calculated separately as functions of τ_0; φ is then the parameter.

Proceeding in the manner outlined above we find from (4) and (5):

$$i = \frac{V_{\max}}{\omega L} \left\{ \cos \tau_o - \cos \tau - q (\tau - \tau_o) \right\} \quad . \quad . \quad . \quad (8)$$

and from (6) and (8) it follows that:

$$0 = \cos \tau_o - \cos \tau_d - q (\tau_d - \tau_o) \quad . \quad . \quad . \quad . \quad . \quad (9)$$

By now introducing two auxiliary angles x and y:

$$x = {}^1\!/_2 (\tau_d - \tau_o), \quad y = {}^1\!/_2 (\tau_d + \tau_o), \quad . \quad . \quad . \quad (10)$$

we may write (9) in the following form:

$$q = \frac{\sin x}{x} \sin y, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

If we ignore the arc voltage with respect to the direct voltage V_0', that is to say if we ignore the difference between V_0' and V_0, then by substituting (8) in (7) and using this in combination with (10) we arrive at

$$\operatorname{tg} y = \frac{\operatorname{cotg} \varphi}{\pi} \cdot x \cdot (x \operatorname{cotg} x - 1) \quad . \quad . \quad . \quad . \quad . \quad (12)$$

For various values of the parameter φ, (12) yields corresponding values for x and y, thus of τ_0 and τ_d. Finally from (11) we get the corresponding values of q.

The result, $\tau_d = \mathrm{f}\ (\tau_0)$ and $q = \mathrm{f}\ (\tau_0)$, with φ as parameter, is represented in *figs. 3* and *4* respectively. From q follows immediately the direct voltage: $V_0' = qV_{\max} - v_{\text{arc}}$. Since the arc voltage is generally small compared with the rectified voltage, the curves of fig. 4 may be taken as the so-called regulating characteristics, representing the trend of the rectified voltage as a function of the ignition angle.

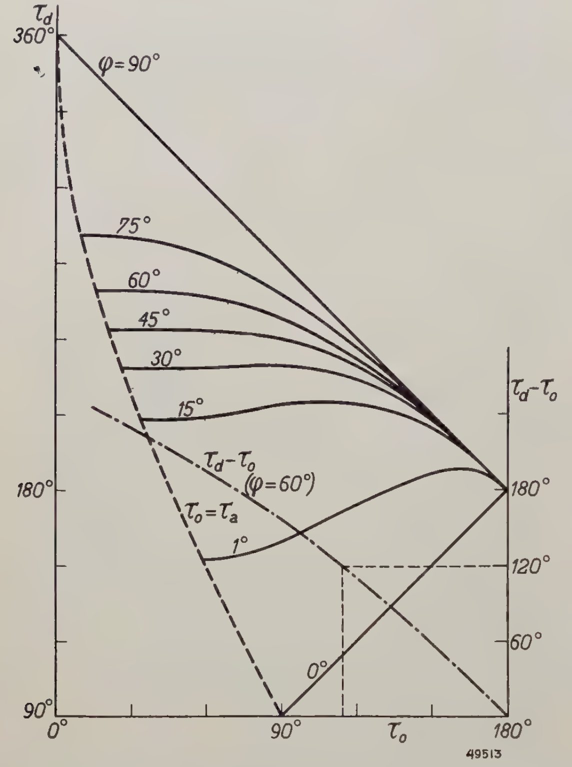

Fig. 3. **Full curves**: extinction angle τ_d as function of the ignition angle τ_0. Parameter $\varphi = \mathrm{tg}^{-1}\,\omega L/R = 0\text{-}90°$ (the index 1 for arc indicates that an angle in the first quadrant is meant). **Dotted line**, at which the curves end: mathematical points where $\tau_0 = \tau_a$ (τ_a is the angle at which the anode of the relay valve becomes positive). The area to the left of the dotted line corresponds to conditions where the anode is negative and the valve cannot ignite. **Dot-dash line**: duration of the current impulse, $\tau_d - \tau_0$, for $\varphi = 60°$.

A valve can only ignite when the anode is positive with respect to the cathode. If the valve is a relay valve with a control grid then a second condition has to be satisfied for the ignition, *viz.* the grid voltage must lie above a certain critical value, which generally is a function of the momentary value of the anode voltage and which is only of importance when the anode voltage is positive. Now the anode voltage is only positive at the moment t_a at which the transformer voltage exceeds the direct voltage at the condenser, thus at an angle of $\omega t_a = \tau_a$ in the first quadrant, for which applies: $V_{\max} \sin \tau_a = V_0'$, or $\sin \tau_a = V_0'/V_{\max}$, which is approximiately equal to q when $v_{\text{arc}} \ll V_0'$. The valve cannot be ignited earlier than what corresponds to τ_a. This explains why the curves in figs. 3 and 4 end on the dotted limit curves on the left-hand side, these limit curves being defined by $\tau_0 = \tau_a$; in fig. 4 this curve is part of a sine line.

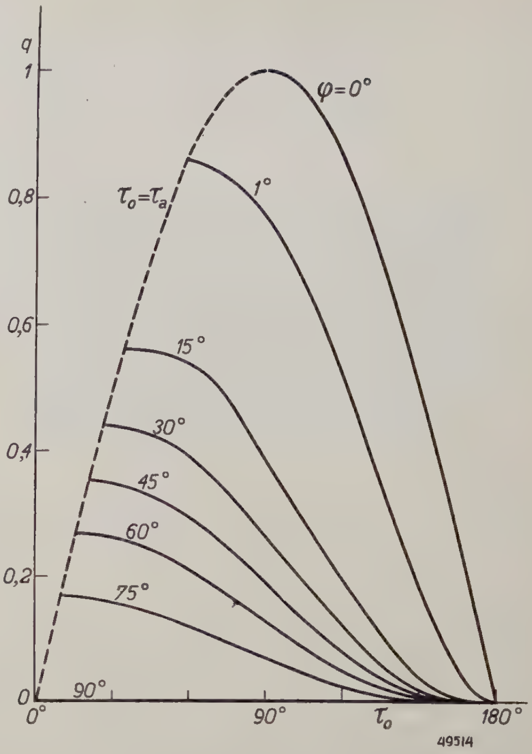

Fig. 4. The relation q (approx. equal to the direct voltage V_0' divided by the top value $V_{\max}$ of the alternating voltage) as a function of τ_0, with φ as parameter. The dotted line again corresponds to the earliest possible ignition ($\tau_0 = \tau_a$).

The factors ($\sin \tau_0 - q$) and ($\sin \tau_d - q$) occurring in (2) and (3) respectively can now be calculated from figs. 3 and 4 as functions of τ_0, with φ as parameter. In this way we find the curves given in *figs. 5* and *6*. The size of the voltage impulses

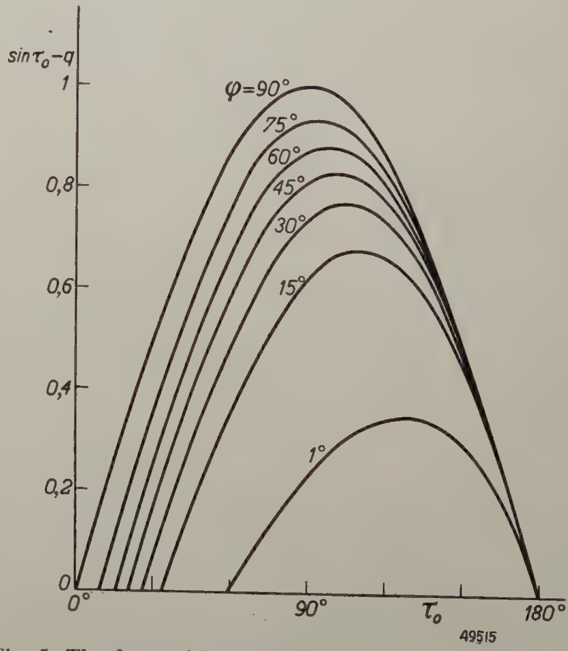

Fig. 5. The factor ($\sin \tau_0 - q$) by which the voltage impulses upon ignition are proportional, as function of the ignition angle τ_0, with φ as parameter. Large values occur at $\varphi \approx 90°$ (strongly inductive circuit) and $\tau_0 \approx 90°$ (ignition at the top of the alternating voltage).

upon ignition and extinction is found by multiplying the values taken from *figs. 5* and *6* respectively by a factor of $V_{\max}L_a/(L_0 + L_a)$ or $V_{\max}L_0/(L_0 + L_a)$, according to whether we are concerned with the transformer coil or the choke coil.

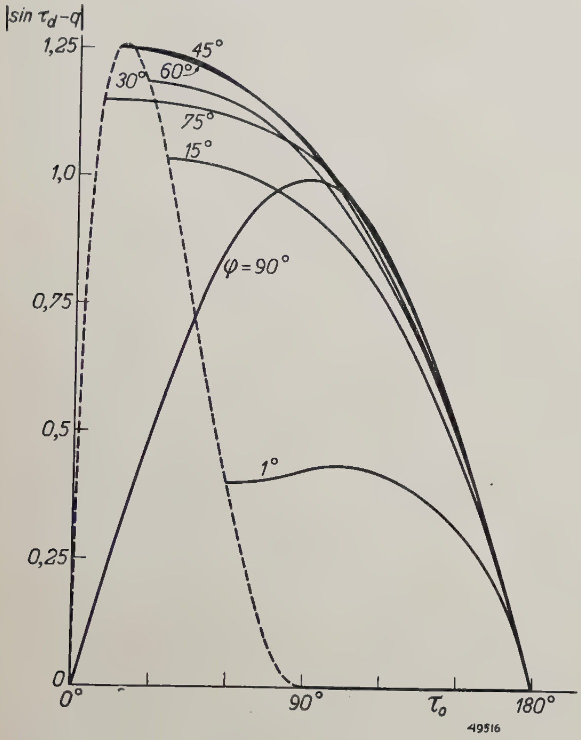

Fig. 6. The factor $|\sin \tau_d — q|$ by which the voltage impulses upon extinction are proportional, as function of the ignition angle τ_0, with φ as parameter. The curves end to the left on the dotted limit line, for which the equation (13) applies; this has a maximum of 1.26 at $\tau_0 = 18°$. The extinction impulses are large with many combinations of φ and τ_0 where $\varphi \approx$ 15°-90°, $\tau_0 \approx$ 15°-120°.

From fig. 5 it may be seen that the ignition impulses are large when in a strongly inductive circuit ($\varphi \approx$ 45°-90°) the ignition takes place roughly at the peak of the alternating voltage ($\tau_0 \approx 90°$). The factor $\sin (\tau_0 — q)$ is maximum 1, which value occurs for $\varphi = 90°$, $\tau_0 = 90°$.

In fig. 6 the curves end at the left on the dotted limit curve, the equation for which reads [2]):

$$\cos \tau_d - \tau_d \cdot \sin \tau_a = \cos \tau_a - \tau_a \cdot \sin \tau_a. \quad (13)$$

The function given by (13) shows a maximum, amounting to 1.26, at $\tau_0 = 18°$, $q = \sin 18° = 0.31$, to which correspond $\tau_d = 252°$, $\varphi = 53°$. The voltage jumps occurring upon extinction of the valve are therefore greatest for this combination. With many combinations within wide ranges of φ and τ_0, however, — $\varphi \approx$ 15°-90°, $\tau_0 \approx$ 15°-120° — they are not much less than this maximum.

Finally *fig. 7* shows the trend of the quantities v, v', i and $\omega L\, \mathrm{d}i/\mathrm{d}\tau$ as functions of τ for the case where $\varphi = 30°$, $\tau_0 = 60°$. Here the two voltage jumps are clearly seen.

Rectifier working on an *m*-phase system of alternating voltages

The system just described (fig. 1) can hardly be considered for a power supply to transmitters, because, among other reasons, in view of the strong pulsation of the rectified current the self-inductance L_0 and the capacity C_0 must have high values to reduce the ripple voltage at the output terminals

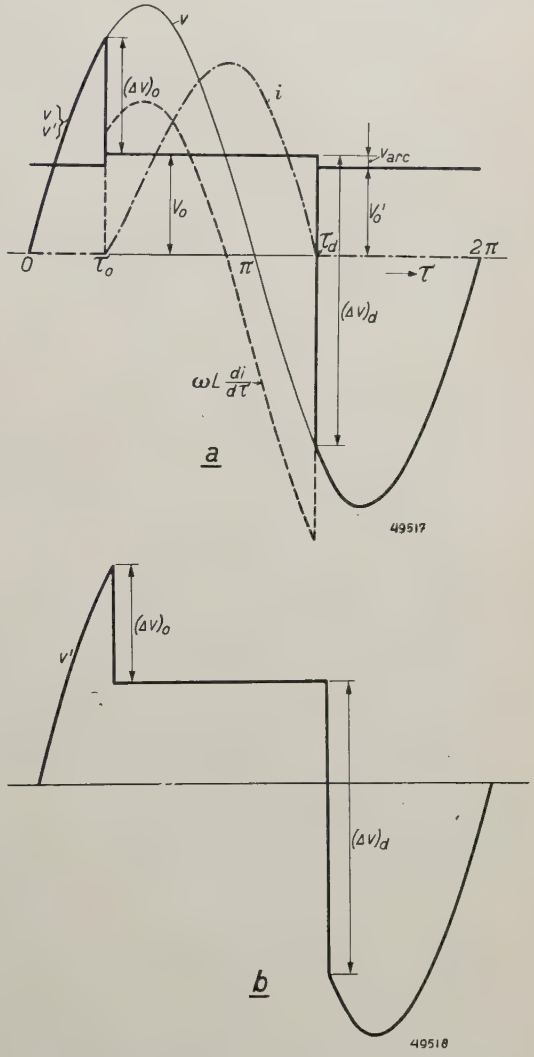

Fig. 7. Voltages and currents as functions of τ in a rectifier according to fig. 1, with $\varphi = 30°$, $\tau_0 = 60°$, to which correspond, according to fig. 3, $\tau_d = 229°$ and, according to fig. 4, $q = 0.39$.
a) Light sine line: feeding alternating voltage v; dot-dash line: current i; dotted curve: voltage at the self-inductance, $\omega L\, \mathrm{d}i/\mathrm{d}\tau$. It is here assumed that $L_0 = 0$, thus $L = L_a$. The terminal voltage v' (heavy line) is then, during the passage of current ($\tau_0 < \tau < \tau_d$), equal to $v — \omega L \mathrm{d}i/\mathrm{d}\tau = V_0 = V_0' + v_{\mathrm{arc}}$; before and after the passage of current ($\tau < \tau_0$ respectively $\tau > \tau_d$) $v' = v$. At $\tau = \tau_0$ an ignition impulse $(\Delta v)_0$ arises in the terminal voltage, and at $\tau = \tau_d$ an extinction impulse $(\Delta v)_d$.
b) Here the trend of v' is shown separately.

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[2]) This follows from the relation (9) between τ_0, τ_d and q as applied to the limit case of the earliest possible ignition: $\tau_0 = \tau_a = \sin^{-1} q$, where the index for arc indicates an angle in the first quadrant.

below the admissible maximum. In such cases one always chooses a rectifying circuit fed from a symmetrical multi-phase system. The number of phases m is usually 2, 3, 4 or 6. For $m = 3$ a circuit is given in *fig. 8*. The grid alternating voltages must likewise form a system of m-phases in the same order of succession as the system of anode voltages.

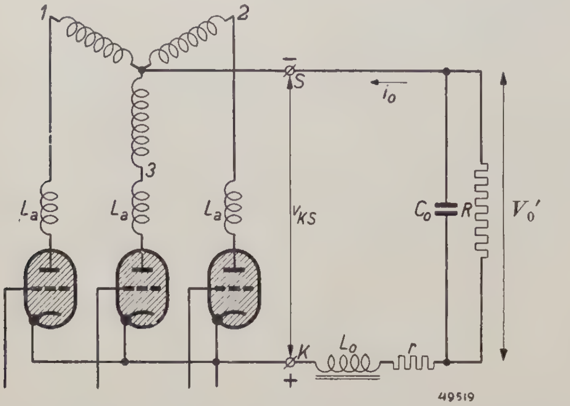

Fig. 8. Circuiting of a rectifier fed from a three-phase system of alternating voltages. L_a = leakage inductance per branch.

Simplified case: no leakage and only resistance in the external circuit

We will begin the study of this circuit by considering a very simplified case. For the present we will assume that in the three-phase circuit of fig. 8 the self-inductances L_a and L_0 and the capacity C_0 are zero, so that there is only the resistance $(R + r)$ in the external circuit. The transformer voltages are assumed to be sinusoidal, also when the system is loaded; the arc voltage is taken to be negligible.

We will start with a "late" ignition moment, *i.e.* with the ignition angle τ_0 but little less than 180°, and then see what happens when the ignition is gradually advanced.

In *fig. 9* the light sine lines indicate the voltage variation of the anodes with respect to the star point S (the negative pole). The heavy curves represent the trend of the voltage of the cathodes K (the positive pole) with respect to S, in particular in the case (a) for $\tau_0 = 135°$. Considering that this voltage is proportional to the current flowing through the resistances R and r, these curves likewise give a graphical representation of that current, which, as is seen, consists of three impulses per cycle. Through each of the valves a current flows consisting of only one such impulse per cycle.

If, now, we cause the ignition gradually to take place earlier then for $\tau_0 = 60°$ we reach the situation sketched in fig. 9*b*, where the dead interval between the impulses is reduced to zero, so that each of the impulses covers exactly 1/3 of the cycle. Upon τ_0 being further reduced (fig. 9*c*) the duration of the impulse remains 1/3 of a cycle, this being explained in the following way. After the ignition of a valve, for instance that in the branch *1*, the voltage v_1 of the respective transformer coil is greater than the voltage v_3 supplied by the coil preceding *1* in phase (see fig. 9*c*, *e.g.* at τ'). Since the higher voltage v_1 prevails also between the direct current terminals S and K, the anode voltage of the valve in branch *3*, v_3—v_1, is negative. This valve must therefore have become dead as soon as the valve in branch *1* was ignited. In each valve of the rectifier the live period is thus exactly 1/3 cycle (in general $1/m$). The extinction angle τ_d, which up to $\tau_0 = 60°$ was constant (180°), now becomes equal to $\tau_0 + 120°$.

This continues to apply until at $\tau_0 = 30°$ we get the situation outlined in fig. 9*d*. At $\tau < 30°$ (*e.g.* τ'' in fig. 9*d*) the anode voltage of the valve in branch *1*, v_1—v_3, is still negative. Fig. 9*d* therefore represents the case where the ignition is advanced as far as possible.

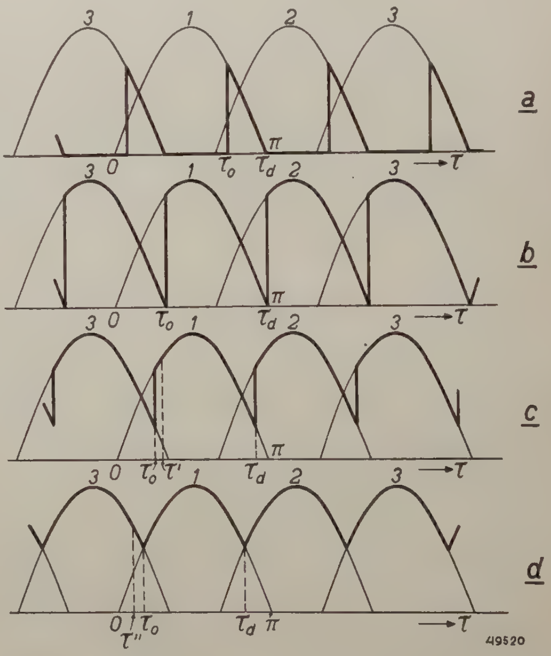

Fig. 9. Voltages and currents as function of τ for a rectifier according to fig. 8, where $L_a = 0$, $L_0 = 0$, $C_0 = 0$. Light lines: positive halves of the sinusoidal voltages of the coils *1*, *2* and *3*; heavy lines; voltage of K with respect to S, also current in the external circuit. The ignition angle τ_0 varies between 135° and 30°.

a) $\tau_0 = 135°$, the current impulse being of a shorter duration than 1/3 cycle, the current in the external circuit showing interruptions.

b) $\tau_0 = 60°$, c) $\tau_0 = 45°$, d) $\tau_0 = 30°$: the current impulses last 1/3 cycle, the current in the external circuit flowing without interruption. The case (b) is the border line between interrupted and continuous current. At (d) the ignition is as early as possible and the direct voltage obtained is as large as possible.

The area enclosed between the heavy curves in figs. 9*a-d* and a part of the τ axis of the length of one cycle is the greatest possible in fig. 9*d*. Since this area is a measure for the average voltage supplied by the rectifier, this voltage is highest with the earliest possible ignition.

One can therefore distinguish two working conditions of the rectifier according to the shape of the current in the external circuit:

1) that with interrupted current: duration of impulse $\tau_d - \tau_0 < 2\pi/m$; ignition "late" ($\tau_0 > \pi - 2\pi/m$);
2) that with continuous current: duration of impulse $\tau_d - \tau_0 = 2\pi/m$: ignition "early" ($\tau_0 < \pi - 2\pi/m$).

In this simple case where there is no self-inductance there are no voltage jumps at the transformer.

The case with leakance and with self-inductance and inverse voltage in the external circuit

We will now return to the circuit of fig. 8 more closely approaching the reality, where the leakage inductances L_a and the equalising self-inductance L_0 and capacity C_0 can no longer be assumed to be zero. We will take C_0 of such a value that the voltage at the terminals of C_0 and R may be regarded as a ripple-free direct voltage V_0'. We can again make the above-mentioned distinction between working conditions with interrupted current and with continuous current, although it is not so easy to indicate as in the case of fig. 9 at what value of τ_0 the transition takes place between the two conditions. It will be evident, however, that with interrupted current the m branches act entirely independently of each other, so that what has been deduced above for fig. 1 applies equally to each of them. Consequently ignition peaks again arise according to equation (2) and extinction peaks according to equation (3), such once per cycle at each self-inductance L_a, but m times per cycle at the self-inductance L_0 (with a factor L_0 instead of L_a in the numerator). The extinction angle is now no longer equal to π, as in the simple case of fig. 9*a*, but a function of τ_0 and φ as represented in fig. 3. Instead of τ_d one may plot the impulse duration $\tau_d - \tau_0$ as a function of τ_0; in fig. 3 this has been done by way of example for one value of φ (= 60°). When for a given value of φ, τ_0 is reduced from π onwards then the impulse duration $\tau_d - \tau_0$, increasing from 0, reaches at a certain point the value $2\pi/m$; here the successive valve currents join up to each other. The value of τ_0 at which this happens is a function of the number of phases m and of φ. From fig. 3 it is to be seen that for $m = 3$ and $\varphi = 60°$ the limit lies at $\tau_0 = 114°$.

Upon τ_0 being still further reduced the impulse duration $\tau_d - \tau_0$ does not remain constant at $2\pi/m$ as in the leakance case of fig. 9 but may increase slightly. That this is possible is due to the leakage inductances L_a. Let us consider any one of the m branches, which we will call *1*, at the moment that it takes over from the preceding branch (this then being the *m*th). Whereas in the case of $L_a = 0$ the current suddenly passes over from branch m to branch *1* (*fig. 10a*), with infinite values of L_a this commutation is gradual (fig. 10*b*): upon the ignition of the relay valve *1* the current i_1 in branch *1* begins to expand and the current i_m in branch m decreases. The commutation is ended when the diminishing current (in this case i_m) has reached zero.

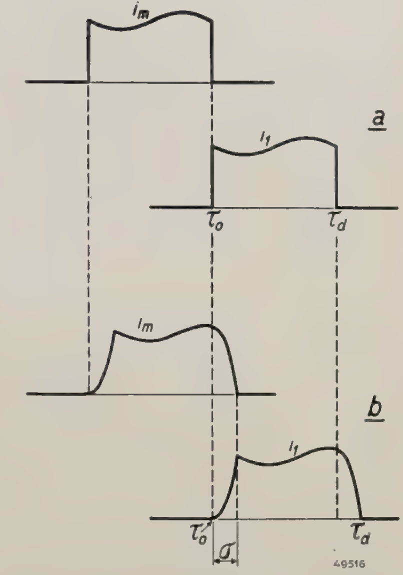

Fig. 10. Commutation of the current from branch m to branch *1*. *a*) without leakance ($L_a = 0$): i_m is abruptly superseded by i_1; *b*) with leakance: the commutation proceeds gradually, in an interval σ.

To calculate the voltage jumps occurring we have to analyse the situation existing during the commutation. In order to avoid unnecessary complications we will again introduce an approximation which is usually justified in practice: we assume that the current i in the external circuit is constant, that is to say free of ripple, and thus equal to the mean value I_0 of the rectified current.

During the commutation, which, expressed in angles, occupies an interval σ, the equation applying for the circuit formed by the transformer coil *1*, the valve *1*, the valve m and the coil m is

$$V_{\max}\sin\tau - \omega L_a\frac{\mathrm{d}i_1}{\mathrm{d}\tau} + \omega L_a\frac{\mathrm{d}i_m}{\mathrm{d}\tau} - V_{\max}\sin\left(\tau+\frac{2\pi}{m}\right) = 0, \tag{14}$$
$$(\tau_o < \tau < \tau_o + \sigma).$$

Since, further, $i_m = i - i_1$ and $\mathrm{d}i/\mathrm{d}\tau$ according to the approximation just introduced may be taken as equal to zero, after a small reduction it follows from (14) that:

$$\omega L_a\frac{\mathrm{d}i_1}{\mathrm{d}\tau} = -V_{\max}\sin\frac{\pi}{m}\cos\left(\tau+\frac{\pi}{m}\right). \tag{15}$$

During the commutation interval referred to the terminal voltage of coil *1* has a value of $V_{\max}\sin\tau - \omega L_a \mathrm{d}i_1/\mathrm{d}\tau$. Immediately before this interval there was no load on coil *1* and thus it had a terminal voltage of $V_{\max}\sin\tau$. Immediately after the interval it is loaded with the full current $i = I_0$, which, however, owing to its being constant does not give rise to any voltage loss in L_a; thus the terminal voltage of coil *1* is then also given by $V_{\max}\sin\tau$. The magnitude of the jumps at the beginning (τ_0) and at the end ($\tau_0+\sigma$) of the commutation from branch *m* to branch *1* amounts according to (15) to:

$$\left.\begin{aligned}(\Delta v_1)_{\tau_o} &= V_{\max}\sin\frac{\pi}{m}\cos\left(\tau_o+\frac{\pi}{m}\right),\\ (\Delta v_1)_{\tau_o+\sigma} &= -V_{\max}\sin\frac{\pi}{m}\cos\left(\tau_o+\frac{\pi}{m}+\sigma\right).\end{aligned}\right\} \tag{16}$$

We notice that the ignition impulses are only dependent upon τ_0 and not L_a; they are zero for $\tau_0 = \pi/2 - \pi/m$, *i.e.* with the smallest possible ignition angle. At the end of the commutation the impulses are indeed dependent upon L_a, since σ increases with L_a; under normal conditions, however, σ is a small angle (of the order of a few degrees), so that these impulses, except for their polarity, are approximately equal to those at the beginning of the commutation.

Equally large jumps but of opposite sign are found in the terminal voltage of the same coil *1* for the commutation from this branch to branch *2*. The terminal voltages of coils of the other $m-1$ branches show the same picture but displaced in phase a whole number of times $2\pi/m$.

We will now consider the voltage v_{KS} on the external circuit, thus between the points K and S (fig. 8). This voltage has the mean value $(R+r)I_0$ but possesses also a large ripple component that is taken up by L_0. One might suppose that from the assumption of a ripple-free rectified current i in the external circuit it would follow that $L_0\mathrm{d}i/\mathrm{d}t = 0$, but generally this is not so, because i (a very special case excepted) can only be constant when L_0 is infinitely large. $L_0\mathrm{d}i/\mathrm{d}t$ therefore does differ from zero.

Immediately before the commutation from branch *m* to branch *1* the voltage between K and S is

$$v_{KS} = v_m \quad \dots\dots\dots \tag{17a}$$

and after it:

$$v_{KS} = v_1 \quad \dots\dots\dots \tag{17b}$$

During the commutation $v_{KS} = v_1 - \omega L_a \mathrm{d}i_1/\mathrm{d}\tau = v_1 - {}^1\!/_2\,\omega L_a\,\mathrm{d}(i_1 - i_m)/\mathrm{d}\tau$, because $i_m = i - i_1$. Substituting here for $\mathrm{d}(i_1 - i_m)/\mathrm{d}\tau$ the value obtained from (14), we get

$$v_{KS} = {}^1\!/_2\,(v_1 + v_m) \quad \dots \tag{17c}$$

thus exactly the average of the voltages of the two branches concerned in the commutation.

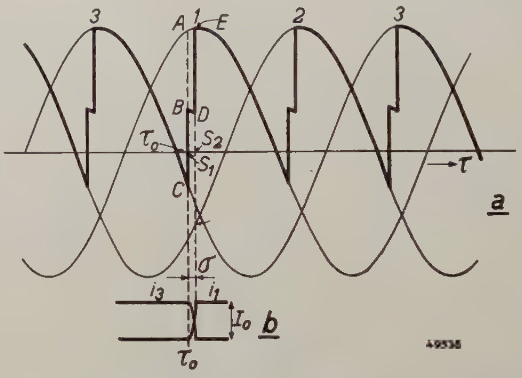

Fig. 11. *a*) voltages, *b*) currents, represented as functions of τ, for a rectifier according to fig. 8, with $\tau_0 = 75°$. Heavy lines in *a*): voltage of K with respect to S. At the beginning of the commutation from branch *3* to branch *1* the following voltage impulses arise: AB in the terminal voltage v_1', CB in the terminal voltage v_3' and also in the voltage v_{KS}. At the end of the commutation v_1' and v_{KS} make a surge DE and v_3' makes a surge D in the curve *3*.

This is all made clear by *fig. 11*, which shows the trend of voltage and of current as functions of τ for the case where $m = 3$, $\tau_0 = 75°$. The heavy line in fig. 11*a* represents the voltage v_{KS} according to the equations (17a, c and b). Fig. 11*b* illustrates the current commutation from branch *3* to branch *1*. (The shape of the currents is found by integrating eq. (15) and making use of the boundary conditions $i_1 = 0$ for $\tau = \tau_0$; $i_1 = I_0$ for $\tau = \tau_0 + \sigma$.) At the moment that the relay valve *1* is ignited ($\tau = \tau_0$) the terminal voltage of coil *1* drops by an amount AB from S_1A to S_1B and the voltage v_{KS} rises by an equally large amount BC from S_1C to S_1B. At the end of the commutation from branch *3* to branch *1* ($\tau = \tau_0 + \sigma$) both the voltages mentioned rise from S_2D to S_2E.

The alternating components of the pulsating voltage v_{KS} are entirely absorbed by L_0 (if we again ignore r). Consequently the voltage impulses found at L_0 are just as large as those at L_a (though sometimes of a different sign), contrary to the case with interrupted current, where the simultaneous voltage jumps at L_a and L_0 are in the ratio of $L_a : L_0$. This is due to the fact that at the moments of the jumps with interrupted current we have the same value of di/dt at L_a as at L_0, whereas with non-interrupted current these values differ.

Influence of parasitic capacities

In the foregoing we have shown that in the normal working of rectifiers voltage impulses occur at the self-inductances. The results found have been recapitulated in *table I*. It is to be noted that not only have some expressly mentioned approximations been introduced but that we have also tacitly passed over the various details. For instance we have not considered conditions where more than two valves are working simultaneously. Impedances on the primary side of the transformer have been assumed to be zero; nothing has been said about the manner in which the primary coils are circuited (in delta, in star, etc). More complicated connections, such as those of Grätz, which are often applied in practice (see for instance the first of the articles cited in footnote [1]), have not been dealt with, because a closer investigation shows that they may be replaced by equivalent circuits of the type in fig. 8. There is no need to go into all these finesses here.

Table I. Summary of the magnitude of the voltage impulses on L_a and L_0 in the absence of parasitic capacities. No attention has been paid to the polarity because this is of no consequence for our considerations.

<table>
<tr><th>Working condition</th><th></th><th>Ignition</th><th>Extinction</th></tr>
<tr><td rowspan="2">Interrupted current</td><td>In L_a:</td><td>$\frac{L_a}{L_0 + L_a}(\sin \tau_o - q)\,V_{\max}$</td><td>$\frac{L_a}{L_0 + L_a}(\sin \tau_d - q)\,V_{\max}$</td></tr>
<tr><td>In L_0:</td><td>$\frac{L_0}{L_0 + L_a}(\sin \tau_o - q)\,V_{\max}$</td><td>$\frac{L_0}{L_0 + L_a}(\sin \tau_d - q)\,V_{\max}$</td></tr>
<tr><td rowspan="3">Continuous current</td><td rowspan="2">In L_a:</td><td>$\sin\frac{\pi}{m}\cos\left(\tau_o + \frac{\pi}{m}\right) V_{\max}$</td><td>$\sin\frac{\pi}{m}\cos\left(\tau_o + \frac{\pi}{m} + \sigma\right) V_{\max}$</td></tr>
<tr><td colspan="2">and equally large impulses a time $\frac{2\pi}{\omega m}$ later</td></tr>
<tr><td>In L_0:</td><td colspan="2">The same as in L_a</td></tr>
</table>

A consideration of the formulae given in table I will show that none of the voltage impulses can be much greater than $V_{\max}$ and that in most cases they may even be much smaller. Notwithstanding these impulses, the potential difference between the ends of a secondary transformer coil is never greater than $V_{\max}$. Nevertheless, disruptions have occurred in transformers whose insulation should be taken to be absolutely proof against a top voltage $V_{\max}$. How are these to be explained? The answer is to be sought in a factor not yet taken into account in our considerations, namely the presence of parasitic capacities.

These capacities affect the situation in various respects, although generally speaking they are so small that they need not be considered in the equation (1) for the main current i. In the first place they form oscillating circuits with the self-inductances (L_a or L_0) to which they are connected in parallel. These circuits are excited by the voltage impulse and oscillate in their own frequency, which is usually much higher than the mains frequency. Consequently it is no longer correct to say, as in the preceding paragraph, that the voltage across a transformer coil cannot be greater than $V_{\max}$. In a fraction of a cycle of the mains frequency the voltage on the oscillating circuit is opposite in polarity and combines with the momentary value of the transformer voltage. *Fig. 13* gives the oscillogram of the circuit of *fig. 12*, where the oscillations are clearly seen. Since the voltage peak is rapidly repeated a number of times this involves the risk of a step-like disruption.

A second effect of the presence of the parasitic capacities is their influence on the distribution of the voltage impulses, in particular the distribution among the individual windings of the secondary transformer coils or of the choke coil. The fact that a voltage impulse may be distributed very unevenly among the windings was known already in the times when it first became the practice to employ overhead cables for high tensions and it

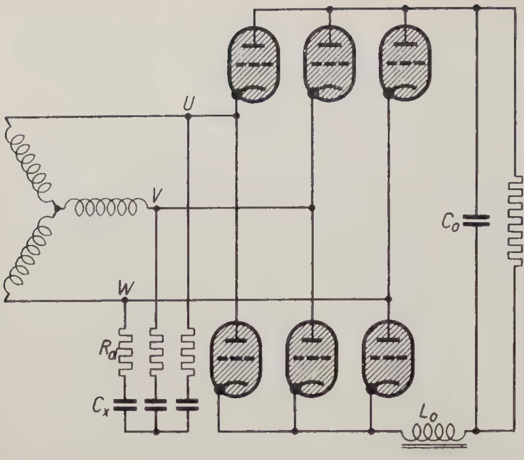

Fig. 12. Circuit according to Grätz, the voltage on which between the points U and V is represented in the oscillograms of figs. 13 and 16. The functions of the capacitors C_x and the damping resistance R_d will be discussed farther on.

was found that when struck by lightning the insulation of the outermost windings of the transformers connected to these overhead cables most frequently showed the worst damage [3]).

To get an idea of this effect it does not suffice simply to regard the parasitic capacities as capacities connected in parallel to the coils. Rather we have to consider that adjacent windings have a capacity both mutually and in respect to earth. Thus we arrive at a replacement system as given in *fig. 14*, where these capacities are indicated by K and C respectively. The result is that a sudden change in voltage at the end a of the coil does not by any means at first distribute itself evenly over the whole coil, but that the windings at the end a receive a disproportionately large part of the voltage impulse, so that there the insulation is endangered. The voltage distribution is all the more irregular according as the voltage at the point a changes more quickly.

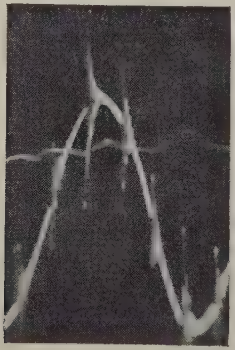

Fig. 13. Photo of an oscillogram of the voltage between U and V in a rectifier according to fig. 12, for $C_x = 0$ and $R_d = 0$. The voltage surges occurring when commuting excite oscillating circuits formed by leakage inductance and parasitic capacity.

That there is no need to worry about the polarity of the voltage impulse (compared with the sign of $V_{\max} \sin \tau$ at the moment at which the impulse occurs) will be evident, in view of the fact that a few windings between which there is normally only a small fraction of the voltage $V_{\max} \sin \tau$ are loaded with the full voltage impulse.

It is not only this "internal" distribution of the impulse that is affected by the capacities, but also the fractions which the choke coil or the transformer each take for their account. In the non-capacity case, with interrupted current, these fractions were $L_a/(L_0 + L_a)$ and $L_0/(L_0 + L_a)$. Without going into it more closely here it will be evident that particularly at the first moment the capacities may entirely change these ratios.

Precautions against the danger of voltage impulses

We will now discuss some measures that should be taken to minimise the danger of voltage impulses.

A most obvious means is the extra insulating of the outermost windings of the secondary transformer coils, known from olden times, but this is not always practicable. The aim will therefore be to keep the impulses themselves as small as possible. It will then be necessary to distinguish between the condition existing while the transmitter is being started up, when the direct voltage is gradually raised from zero, and the normal working condition when the direct voltage is practically the maximum that can be supplied by the rectifier. As the direct voltage is increased, the ignition angle τ_0 changes, passing through a series of values from about π to a certain minimum, thereby passing the value where the condition of interrupted current changes into that of a continuous current. Let us first give attention to the normal working condition where the current is not interrupted. At the beginning and end of each commutation impulses occur of an amplitude which according to eq. (16)

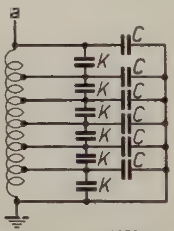

Fig. 14. Replacement diagram of a coil with parasitic capacitors K between adjacent windings and parasitic capacitor C of the windings with respect to earth.

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[3]) See for instance K. W. Wagner, Das Eindringen einer elektromagnetischen Welle in eine Spule mit Windungskapazität, E.u.M., **33**, 89-92 and 105-108, 1915.

is proportional to $\cos(\tau_0 + \pi/m)$ and $\cos\{\tau_0 + (\pi/m) + \sigma\}$ respectively.

As already remarked, the impulses occurring at the beginning of the commutation become zero when $\tau_0 = \pi/2 - \pi/m$, thus when the ignition takes place as early as possible, *i.e.* when the direct voltage is as high as possible. It is therefore advisable to design the rectifier in such a way that this highest direct voltage is at the same time the voltage required. The voltage impulses at the end of the commutation are only small when the ignition takes place as early as possible, being proportional to $\cos(\pi/2 + \sigma)$; σ is usually an angle of only a few degrees.

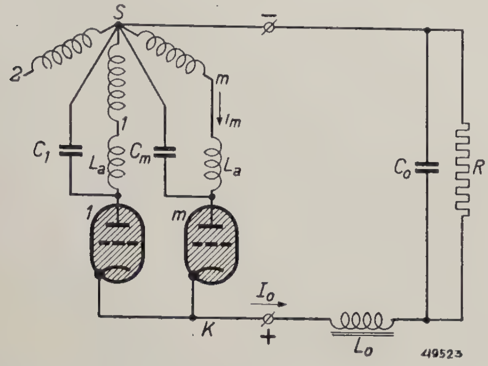


Fig. 15. Two in phase successive branches (*m* and *1*) of a rectifier with *m* phases provided with capacitors $C_1 \dots C_m$. These capacitors reduce the ignition peaks.

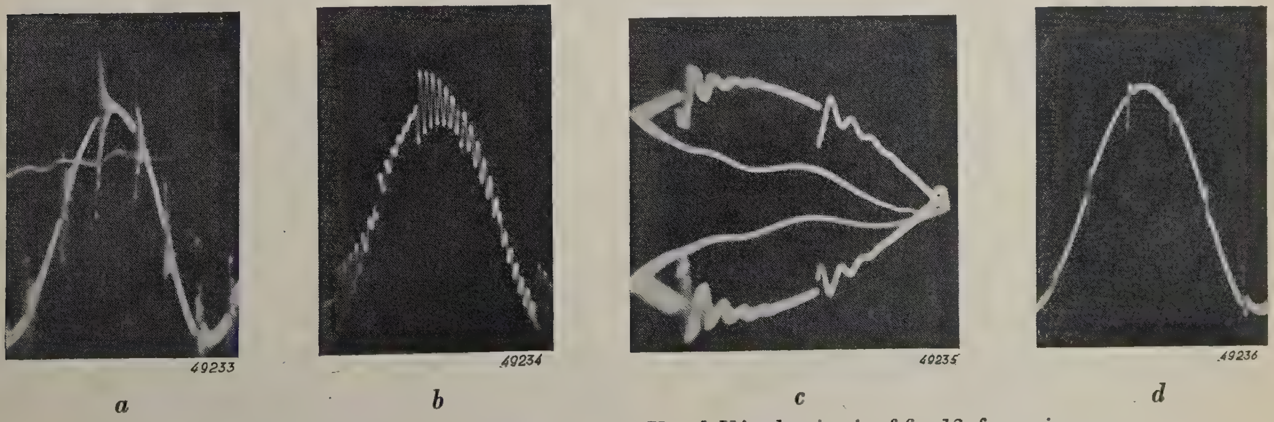
Circumstances may arise, however, which make it necessary to use temporarily a lower working voltage, in which case adjustments have to be made to less favourable values of τ_0. Furthermore, these unfavourable τ_0 values occur every time the voltage is stepped up. Precautions will therefore have to be taken to guard against the accompanying voltage impulses.

The means available, apart from the extra insulation already mentioned, for rendering these voltage impulses harmless may be divided into three groups:

a) condensers parallel to the transformer,
b) chokes in series with the valves,
c) a combination of a) and b),
which should be supplemented with
d) damping resistances.

a) *Condensers parallel to the transformer*

An effective means of attenuating the commutation impulses is to introduce condensers ($C_1 \dots C_m$ in *fig. 15*) between the star point and the anodes of the valves. Just before the valve *1* is ignited the condenser C_1 has a higher voltage than the condenser C_m in the preceding branch. Upon the valve *1* being ignited, a sudden discharge takes place from C_1, mainly because of the circulation of a current through the circuit formed by C_1, the valves *1* and *m*, and C_m. This circuit has practically no self-inductance nor resistance; the current mentioned — which in the valve *m* is opposed to the current $i_m = I_0$ still flowing there — will therefore rise very rapidly and almost immediately reach the value I_0. The current in valve *m* will then have become zero; it cannot reverse its direction and the valve *m* is therefore extinguished; the current i_m in the transformer then flows to C_m. As a result the voltage on this condenser C_m soon rises high enough for the valve *m* to be ignited again, after having been dead for only a small fraction of a cycle. During this second current impulse, which gradually drops to zero, the valves *m* and *1* work simultaneously. Given a sufficiently large



a b c d

Fig. 16. Oscillograms of the voltage between *U* and *V* in the circuit of fig. 12, for various values of C_x and R_d.
a) $C_x = 0$, $R_d = 0$: high voltage peaks with a steep front, followed by a damped oscillation.
b) $C_x = 7000$ pF, $R_d = 0$: lower, less steep peaks, followed by a damped oscillation.
c) $C_x = 7000$ pF, $R_d = 3000$ ohm: front steeper than for (*b*); but damping much greater. (N.B. Time scale differs from that of the other oscillograms, so that the negative half wave is pictured underneath the positive half).
d) $C_x = 7000$ pF, $R_d = 10\,000$ ohms: steep front; damping still greater than for (*c*).

capacity C_x of the condensers $C_1 \dots C_m$, the voltage surges will be smaller than the normal commutation impulses which would arise at L_a if these condensers were not present. This may be seen from the oscillograms of *figs. 16a* and *b* taken from the circuit of fig. 12 for different values of C_x: in (b), where $C_x = 7000$ pF, the largest amplitude of the superposed oscillation is less than that in (*a*), where $C_x = 0$. Of course there is a limit to the value chosen for C_x, because account has to be taken of the cost of these condensers and the load they constitute for the transformer.

The oscillations seen in fig. 16*b* occur in the circuit formed by L_a and C_x. A rough calculation shows that the voltage amplitudes of these oscillations are approximately given by $(1/R) \cdot \sqrt{L_a/C_x} \cdot V_0$. Allowing for a maximum value equal to kV_0, then it follows that

$$C_x \geqq L_a/k^2R^2,$$

in which k may amount, for instance, to 0.2.

The upper limit for C_x follows from the consideration that for reasons of economy it is advisable to keep the component with the mains frequency of the currents flowing through $C_1 \dots C_m$ small in amplitude compared with I_0, say at a maximum of hI_0. Hence it follows:

$$C_x \leqq \frac{h}{\omega R},$$

with h, for instance, = 0.1.

b) *Choke coils in series with the valves*

Another method of safeguarding the transformer consists in connecting up a choke coil (self-inductance L_x) between the ends of each of the secondary transformer coils and the anode of the corresponding valve. In the absence of parasitic and the other extra capacities mentioned under (*a*), then only the fraction $L_a/(L_x + L_a)$ of the voltage impulse excited in the anode circuit will come to lie on the transformer. Actually, however, the parallel capacities that are always present will govern the distribution of the voltage surge. This is all the more favourable, because the parasitic capacities of the choke coil can easily be kept in relation to those of the transformer coil, for instance by making the choke coil without a core and with a greater length than its diameter. By this means it is also easy to make it capable of withstanding the voltage impulses, of which it now has to bear the lion's share.

c) *Combination of parallel condensers and series choke coils*

It is an obvious solution to combine methods (a) and (b). Increasing the parasitic transformer capacity by connecting a capacity C_x in parallel enhances the action of the choke coils, which consequently can be made smaller and cheaper.

d) *The application of damping resistances*

As seen from figs. 16*a* and *b*, owing to the introduction of the capacities C_x the parasitic oscillating circuits die out more gradually. Since in general these oscillations are undesirable, an endeavour will be made to provide for ample attenuation. For the circuit of which L_a forms a part this can be done by connecting the resistance either in series with L_a or in series with C_x, or parallel to C_x. The first would involve larger losses, since the main current would flow through the resistance. The second is less satisfactory because a resistance in series with C_x would prevent this capacitor from supplying the sudden current impulse required for the effect aimed at. This can be seen in figs. 16*c* and *d*, compared with fig. 16*b*: owing to the introduction of the resistance the damping is increased, but there are again steep fronts, which are absent in fig. 16*b*.

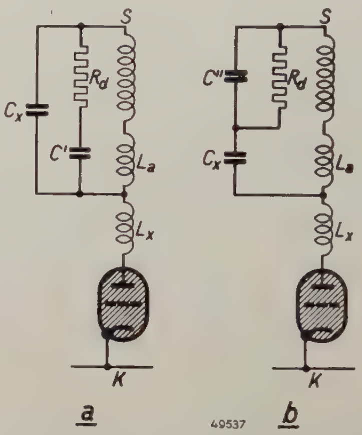


Fig. 17. Two methods of providing the oscillating circuit originally consisting of L_a and C_x with a damping resistance R_d without involving any large loss of energy. In *a*) in series with R_d is a capacitor C' the reactance of which at the frequency f_0 of the circuit is of the order of R_d, but at the mains frequency f large compared with R_d. In *b*) C'' is so chosen that at the frequency f_0 ample damping is provided by R_d and at the frequency f a voltage distributor is formed by C_x and C'' which reduces the voltage with this frequency at R_d.

The connecting of a resistance in parallel with C_x has the drawback that again large losses would occur in the damping resistance, owing to the high tension with the mains frequency present at C_x. This can be avoided by applying the methods of *figs. 17a* or *b* as explained in the text below those diagrams.

The oscillating circuit formed by the choke coil L_x with its parasitic capacity can be damped by connecting a resistance to it in parallel. In the case of the filter choke coil it will be preferable to use a damping resistance in series with a capacitor.

The measures discussed here have been successfully applied in several transmitters, with the result that former troubles from breakdowns owing to disruption of insulations no longer occur.

PHOTOGRAPHING COOLING CURVES OF HARDENING OILS BY MEANS OF A CATHODE-RAY OSCILLOGRAPH 1)

621.785.65:
621.317.35

Steel is usually hardened by first heating it to about 800 °C and then rapidly cooling it by immersion in a liquid (quenching). In this cooling process three successive stages can be distinguished:

1) slow cooling, owing to the metal being more or less insulated by a vapour layer around it;
2) rapid cooling, the vapour having disappeared and the heat being bound by the boiling of the liquid immediately around the metal;
3) slow cooling, after the temperature has dropped to below the boiling point.

For the success of the hardening process it is of great importance that the first two phases should be of short duration to prevent conversion of the austenite. Furthermore, the boiling point of the hardening liquid should be about 400 °C.

It appears that these two requirements can be met by using colza oil, but this, like all vegetable as well as animal oils, has the disadvantage that it changes in composition under the action of oxygen, becoming heavy and sticky and losing much of its originally good cooling property. For this reason mineral oils are usually preferred, although the hardening process is less satisfactory than with colza oil, their greater chemical durability being the decisive factor. Tests have shown that colza oil absorbs more than six times as much oxygen in a given time than does ordinary mineral oil.

The question then arose whether a mixture could not be compounded with a mineral oil as the main constituent and having cooling properties closely approximating those of colza oil but without its drawbacks.

First of all a method of measuring has to be thought out for studying the course of the cooling process. It was found that the method described below proved to be quite satisfactory.

Use was made of a solid silver ball 20 mm in diameter, inside which is a thermo-couple to which the heat of the silver is well conducted. The ball is heated to about 800 °C, the temperature being measured by means of a millivolt meter connected to the thermo-couple. The ball is then immersed in the oil to be tested for its cooling properties. In principle it would then only be necessary to record the reading of the millivolt meter at short intervals and to plot them, converted into temperature equivalents, as a function of time. However, as will be seen presently, the process takes place rather too quickly to allow of this being done with the necessary degree of accuracy; certain phases sometimes last no more than 2 or 3 seconds. This difficulty has been solved by visually recording the electromotive force of the thermo-couple on the screen of a cathode-ray oscillograph and photographing the picture.

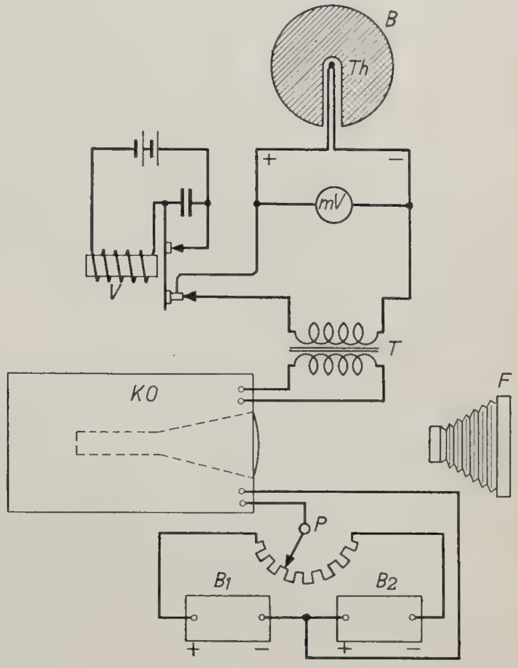


Fig. 1. B = silver ball which, after heating to about 800 °C, is immersed in the hardening medium to be tested. Th = thermo-couple, whose e.m.f. is read from a millivoltmeter and converted into an alternating voltage by means of a vibrator V and a transformer T. This voltage is conducted to the amplifier for the vertical deflection of the cathode-ray oscillograph KO. The voltage for the time base is supplied by means of a potentiometer P, whose arm makes one stroke in the time required (*e.g.* 25 secs) and which is connected to the two batteries B_1 and B_2. F = camera for photographing the oscillograms.

Since the thermo-electric potential is too low to give a direct indication on the oscillograph by direct connection to the plates, it has to be amplified. So as to be able to use the normal amplifier of the oscillograph for amplifying this direct voltage, the latter is converted into an alternating voltage with the aid of a vibrator and a transformer, as illustrated in *fig. 1*; the transformer supplies the voltage conducted to the amplifier of the oscillograph and

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1) The data contained in this article have been taken from an article by B. Levy of Aktiebolaget Wahlén and Block, Stockholm, published in "Electronic Measuring" (1, No. 4, 1946), a Philips periodical dealing with the applications of electronic-measuring technique. The investigations referred to were carried out in cooperation with Svenska Aktiebolaget Philips, Stockholm.

causing the vertical deflection. To get reliable results the vibrator has to be of a robust construction and attention has to be paid to the contacts. Tungsten contacts proved to be unsatisfactory. An alloy of 93% gold and 7% platimun [2]) was found to be highly suitable. Furthermore, the circuit feeding the vibrator has to be well shielded to avoid induction of disturbing voltages in the measuring circuit.

As to the horizontal deflection, the time base of the usual oscillographs cannot be used for this because the phenomenon to be recorded may last 30 to 60 seconds. For this reason the method shown in fig. 1 was employed, where the arm of a potentiometer is rotated by a gramophone motor. Between the motor and the potentiometer spindle is a variable gearing and also an electromagnetic coupling, which, *via* a relay, starts up the potentiometer at the same moment that the silver ball falls into the cooling medium.

Upon the vibrator being started a vertical line appears on the screen of the oscillograph on the extreme left when the potentiometer is in its initial position. The rotation of the potentiometer arm causes this line to change into a more or less sinusoidal line, which gradually diminishes in amplitude as the silver ball cools down. The peaks thus form two symmetrical cooling curves. The picture can easily be photographed, as may be seen from *fig. 2*.

Fig. 2*a* shows the cooling curve of colza oil. The maximum vertical deflection corresponds to 800 °C and the horizontal movement to 23 seconds. One can clearly distinguish here the three phases mentioned in the beginning; the first and second phases, before the temperature drops to about 400 °C, each lasting from 2 to 3 seconds, which is satisfactory for the hardening of steel. In the case of an ordinary mineral oil, however, the first phase takes 12-13 seconds (fig. 2*b*), which is too long for proper hardening.

The recording of a large number of such curves as these has resulted in hardening oils being compounded which have better cooling curves than have been known hitherto. Fig. 2*c* shows the curve for such an oil.

Finally, attention is drawn to another factor of great importance in hardening processes. In this technique it is generally known that hardening oil should be free of water. The trend of the cooling curves clearly shows the effect of traces of water in the oil. Compare the curve of a water-free mineral oil (fig. 2*b*) with that of the same oil but containing 0.2% water (fig. 2*d*); in the latter case the cooling in the second phase is much more intensive, and with such intense cooling cracks in the workpiece will almost inevitably result.

Thus the application of the cathode-ray oscillograph with simple accessories has not only resulted in a better product — here a hardening oil — but it has also made it possible to carry out a simple and sensitive quality test.

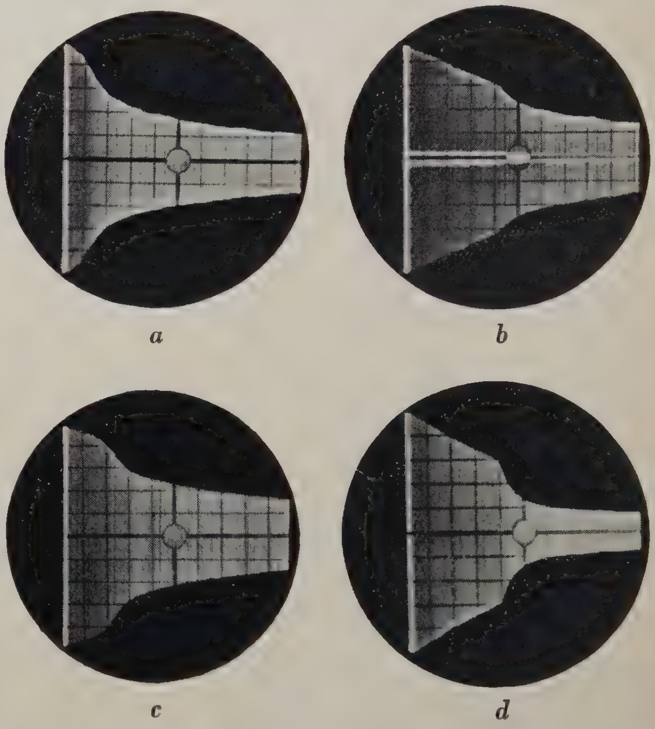
a *b* *c* *d*

Fig. 2. Photographs of cooling curves obtained with different oils. The max. vertical deflection corresponds to 800 °C and the horizontal to 23 secs.

a) Colza oil. The first and second phases (respectively slow and rapid cooling) take together about 5 secs, which is favourable for hardening steel. Owing to their lack of durability, however, vegetable oils are not suitable in practice.

b) A mineral oil. The first phase takes too long, about 13 secs, for steel hardening.

c) The investigations resulted in the compounding of a mixture, with a mineral oil as the main constituent, which combines a satisfactory cooling curve with great durability.

d) Traces of water in the oil affect the cooling curve: the same oil which in the dry state gave the cooling curve (*b*), when 0.2% water is added gives the curve (*d*); in the latter case the cooling in the second phase is so rapid as to cause cracks in the steel workpiece.

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[2]) Benedicks and Härdén, Z. techn. Phys. **13**, 71, 111 166, (particularly 113), 1932.

IN MEMORIAM Dr. P. J. BOUMA.

We should like to pay tribute to the memory of Dr. Pieter Johannes Bouma, born in Amsterdam on 14th April 1908, who died at Eindhoven on 19th January 1947. Bouma was connected with the Philips Laboratory in Eindhoven as an assistant from 1928 until 1930 and as a research physicist from 1933 until his death. From 1930 until 1933 he studied at Utrecht, where in November 1933 under Ornstein he received his degree on his thesis: "Beitrag zur Dynamik der flüssigen Kristalle". Bouma specialized on the theory of illumination and colorimetry, in which fields various publications from his pen have appeared in Physica and in the Proceedings of the "Kon. Ned. Akad. van Wetenschappen". He also wrote many articles for the Philips Technical Review. Furthermore he rendered valuable services to the Netherlands Foundation for Illumination Technology (Ned. Stichting v. Verlichtingskunde).

Since 1940 Bouma had been suffering from a disorder of the central nervous system, which, though it fortunately did not affect his acute intellect, made speaking and writing more and more difficult for him. Nevertheless, between September 1944 and April 1945 he was able to complete the manuscript of his book "Colour Stimuli and Colour Sensations", as well as three other publications.

During 1946 his strength failed him, but he still had the satisfaction of seeing his book in print (it was published in November 1946, and a review of it is given on page 159 of this number).

The following article is a practically unaltered version of a lecture given by Bouma at Utrecht in 1940 for a Vacational Course on "Road and Street Lighting".

THE EDITORS.

PERCEPTION ON THE ROAD WHEN VISIBILITY IS LOW

by P. J. BOUMA †.

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This article deals with the factors affecting perception, when visibility is low, especially as applied to road lighting. The author discusses in turn: contrast sensitivity, distinguishability of the object, speed of perception, glare, uniformity of illumination, the Purkinje effect, and the influence of colours upon perception.

The purpose of road lighting is to make it possible to see objects on the highways. Therefore in planning their illumination we have to take into account the properties of the eye. As will be shown later, the performance of the eye depends very closely upon the level of brightness: generally speaking, the higher this level the better we can see. Therefore it would be desirable to employ very high intensities of illumination on the highways, but this is limited by considerations of economy and in general we are not able to go beyond a few score lux. Compared with the luminous intensities of several times ten thousand lux that we often have during the daytime, this is extremely low. The fact that we can distinguish anything at all is due to the wonderful adaptability of the eye (expansion of the pupil, adaption of the retina); anyhow our vision is still much poorer than it should be with high luminous intensities. Hence it follows that whatever light is available must be used very economically. In other words:

1) We must try to get as much energy as possible (usually electrical energy) for our money's worth.
2) We must get as many lumens as possible per kilowatt input, *i.e.* we must use lamps with a high efficiency.
3) The lumens obtained must be projected on the highway with little loss and in the best possible manner; this means that the most suitable fittings must be used, taking into account the properties of the road surface.
4) In the designing of the lighting system allowance must always be made for the properties of the eye, giving consideration to the two following questions:
   a) under what conditions does the eye function best, and
   b) in how far can these conditions be realized?

The latter problem is often difficult to solve because there are a number of factors over which the illuminating engineer has no control (reflection of the road surface and the objects upon it, surroundings of the road, size of the sources of light, etc.)

We will confine our considerations to point 4) and in particular to what is to be found in literature on point (4a).

For the study of the performance of the eye there are widely divergent methods of approach. This is best illustrated by mentioning two extremes. The one consists in observing the traffic along the lighted roads and from the accident statistics attempting to determine what system of illumination offers the best possibilities of vision. The other extreme consists of a theoretical and laboratory analysis of the process of vision into all its components, then subjecting each component to an experimental investigation and building up from the components a theory of perception on the road; this can be done even without taking a look at a lighted highway. Since both of the methods mentioned have great obvious disadvantages, we shall here attempt to find a golden mean. In our opinion the best compromise is to investigate the components of vision in the laboratory according to the second method and to test the results by repeated practical measurements on the road.

It is in this way that we shall now try to survey a number of important problems connected with vision at the low levels of brightness occurring in road lighting.

Perception

An object on the road is noticed because there is a contrast, *i.e.* because the brightness of an object differs from that of its background, usually the road surface.

Objects can therefore most quickly be perceived when care is taken to provide strong contrasts everywhere, for instance by trying to make all objects appear very dark against a bright background. Since, however, there are a number of factors over which we have no control, this is not always possible. From time to time there will inevitably be such small contrasts as to be hardly perceptible, if at all.

In order to minimise the number of cases where through this cause an object is not noticed at all or else too late, we shall therefore have to provide for conditions where the smallest possible contrast is still just perceptible. By a contrast still just perceptible we mean the ratio $\Delta B : B$, where B is the brightness and ΔB the smallest perceptible difference in brightness. $B : \Delta B$ is called the contrast sensitivity, and it must therefore be made as large as possible.

Upon what condition does contrast sensitivity depend?

In the first place upon the level of brightness. In *fig. 1* the continuous curve gives the relation between contrast sensitivity and brightness [1] [1]). In the problems of road lighting we are mainly concerned with the interval [2]) between 0.1 and 1 candle/m². In this interval the quotient $B : \Delta B$ is found to increase rapidly with the brightness; it varies from 18 to 33, which means that contrasts of 3-5.5% lie on the limit of perceptibility. This continuous curve of fig. 1, however, was measured under the most favourable laboratory conditions, with large light spots on a completely uniform background, with an unlimited time of observation and with the possibility of calm and full concentration, with no disturbing effect from glare.

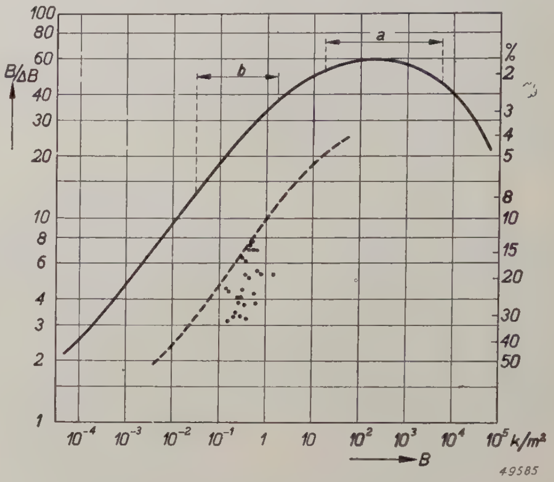

Fig. 1. Dependence of the contrast sensitivity $B/\Delta B$ on the level of brightness B. In road lighting (brightness range b) this is less than in daylight (range a).
Continuous-line curve: laboratory experiment under most favourable conditions.
Dotted-line curve: outdoor measurement taken as dusk was falling.
Scattered dots: measurements taken with good road-lighting installations.

Under practical conditions the contrast sensitivity is therefore much smaller. The dotted line of fig. 1 represents the results obtained under conditions more closely approaching reality: just at dusk, with a uniformly clouded sky, on a road with no artificial illumination the contrast sensitivity was measured [2] for small objects as observed by a pedestrian at a distance of 150 metres; nature provided automatically for the transition through the different levels of brightness. Under these conditions the contrast sensitivity is lower by a factor of more than three.

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[1]) The numbers in square brackets refer to the publications listed at the end of this article.

[2]) 0.1 and 1 candle/m² correspond to the brightness of a dry, light-coloured concrete road surface (reflective power 30%) when it is illuminated with respectively 0.1 and 1 lux (level of illumination with full moon = 0.2 lux).

The dots shown in fig. 1 represent the results of measurements taken under conditions still more closely approaching the reality. Each dot gives the contrast sensitivity under a given lighting installation for the above-mentioned small objects on the brightest part of the road surface. All these measurements refer to "good" lighting installations (with sodium and mercury lamps); they were taken when the road surface was dry [2]. Compared with the dotted line all these contrast-sensitivity points are still lower, as is understandable considering that the non-uniformity of the distribution of brightness and a certain amount of glare play a part as disturbing factors (see below). The fact that some of these points lie almost on the curve and others far below it shows that these disturbing factors are of a greater effect with one installation than with another. Given an installation that is good in every respect, the contrast sensitivity will not lie more than a factor 1.5 below the dotted line, so that at an average level of brightness it will amount to at least 4.5 (*i.e.* contrasts of about 22% will still be visible), while at higher levels of brightness (such as occur with light-coloured concrete roads) it may rise to 6 (17% perceptible contrast), and under favourable conditions even higher.

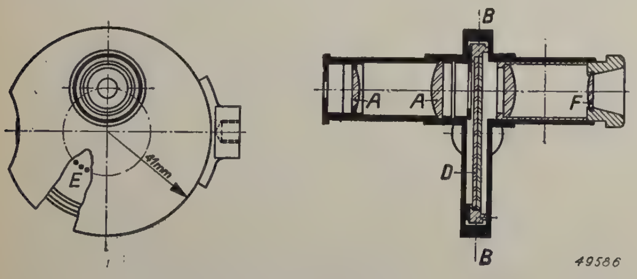

Fig. 2. Visibility meter for road lighting according to Holst and Bouma.

The above measurements with small objects were taken with the help of a so-called visibility meter [3], a diagram of which is given in *fig. 2*. A lens system *AA* focuses the road surface in the plane *BB*. In this plane there is also a rotating glass plate *D*, upon which a number of dots *E* of varying density have been produced photographically. By placing the eye in front of the ocular *F* the road surface and dots are seen focused simultaneously. Upon rotating the disc *D* it is possible to pick out from the different dots passing the field of vision the one that is still just visible, in that way determining the contrast sensitivity. The instrument is so constructed that with the meter in front of the eye the road is observed under practically the same conditions as with the naked eye (enlargement 1 : 1, large field of vision, including any glare from light, small objects, contrast dark on light background, etc.).

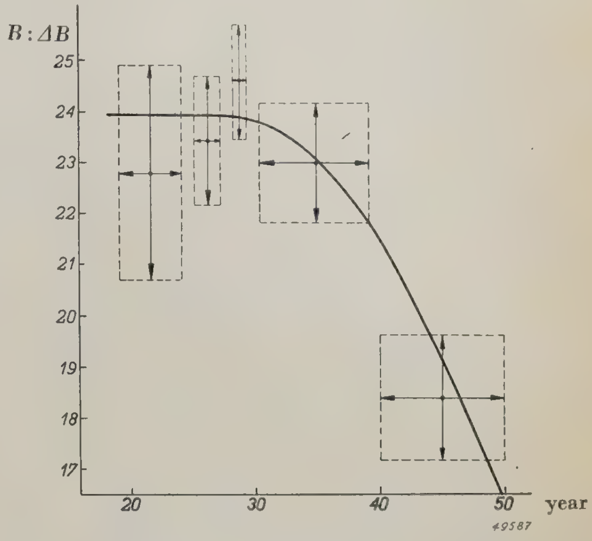

Fig. 3. Average contrast sensitivity as a function of age, measured at a level of brightness of 0.3 candle/m^2, with no source of glare.

Finally it must be noted that the contrast sensitivity is also dependent on age, as is illustrated by the curve in *fig. 3*, taken from an investigation with 100 observers under laboratory conditions [4]. The horizontal arrows give the averaged age groups and the vertical arrows the individual deviations. This dependence on age is even more pronounced in the curve of *fig. 4*, representing the contrast

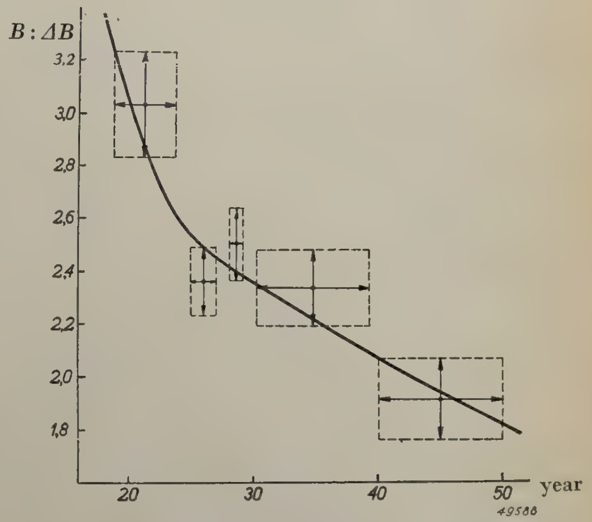

Fig. 4. Average contrast sensitivity as a function of age, measured at a level of brightness of 0.3 candle/m^2 in the presence of a source of glare. The glare causes a much greater decrease in sensitivity to contrast in the older age groups.

sensitivity in the presence of a strong source of glare.

So far we have been speaking only of "just perceptible" contrasts. In practice, however, it is also of great importance that a certain contrast, given by two different brightnesses, lying far above this threshold should be made as striking as possible. Thus the objects are more readily noticed and driving on the road becomes much less of a strain. This can be achieved by eliminating all disturbing influences as far as possible, while also the choice of the kind of light plays a part (see the end of this article).

Recognition

Once an object has been noticed we also want to recognize it as quickly as possible, because our reaction (braking, swerving, sounding the horn) very often depends upon the nature of the object. This recognition is closely related to the visual acuity, *i.e.* the ability of the eye to determine the shape of the object by the look of small details (it is usually only a question of the outline of the object). As a measure of the visual acuity G we may take the inverse ratio of the minimum value of the angle of vision within which a detail must be seen to be observed, or a quantity proportional thereto. This value G is limited on the one hand by the structure of the retina of the eye, thus by the size of the separate light-sensitive elements, and on the other hand by the focusing errors of the eye (spherical and chromatic aberration, diffraction, etc.). It is remarkable how all of these effects cause errors of the same order of magnitude: in this respect the eye makes a wonderful compromise.

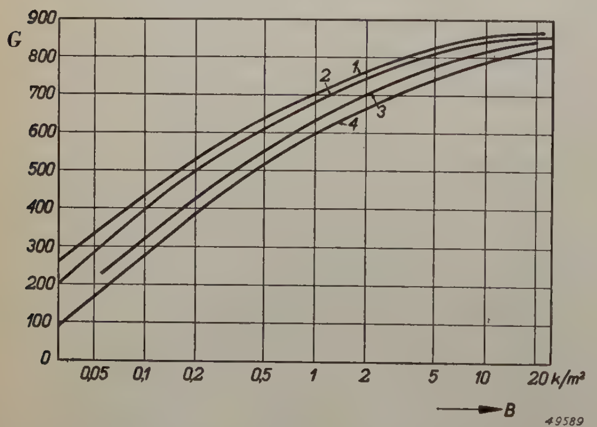

Fig. 5. The dependence of visual acuity G on the brightness B for different kinds of light, *viz 1* for mercury light, *2* for sodium light, *3* for neon light, *4* for incandescent lamp light. The value of the visual acuity G is expressed here as the distance in cm at which circles and squares 1 cm in diameter can just be distinguished. The value $G = 690$ thus corresponds to the capability of just seeing a detail within an angle of vision of about 1 minute.

The effects mentioned have, for example, the result that when looking at a figure consisting of parallel alternating black and white stripes, the parts of the retina upon which the image of the black stripes is formed also receive some light, so that the contrast may be only 70% instead of 100%.

When the level of brightness is lowered then G is reduced [5]. *Fig. 5* illustrates this decrease for different kinds of light.

The cause of the decrease lies partly in the expansion of the pupil; with levels of brightness such as occur in road lighting the pupil diameter is about $2^1/_2$ times as large as in daylight and the effect of the focusing errors is then greater.

At very low levels of brightness visual acuity is affected also by the transition from cone vision to rod vision (see below).

Under laboratory conditions and at high levels of brightness it is just possible to observe details within an angle of vision of about 1 minute. With road lighting, even under favourable conditions, it will not be possible to reach much lower values than 3 minutes. (This is the angle within which an object of 13 cm is seen at a distance of 150 metres.)

Quick recognition

It is particularly of importance for fast traffic that objects on the road can be recognized quickly. It is in fact a question of the time elapsing between the moment when the object comes into the field of vision, under sufficiently favourable conditions for observation, and the moment of reaction to what is seen (braking, swerving, etc.). This period of time may be divided into four parts:

a) The time taken for the image to be built up on the retina. This depends (just as in the case of a photographic plate) very closely on the intensity of the light. We can obtain some insight into this by measuring the time τ during which an object must have been visible in order to recognize it again; τ is thus analogous to the exposure time for a photographic plate. The value $1/\tau$ is often called the velocity of observation. *Fig. 6* gives the relation between $1/\tau$ and the brightness B : curve *1* for sodium and mercury light and curve *2* for incandescent electric light. It is seen that at high levels of brightness we have extremely small values of τ, while at the level of brightness on the road (0.1-1 candle /m²) the time τ usually lies between 1/4 and 1/20 sec, in the case of objects with little contrast, or where there is any intense glare considerably longer times may occur.

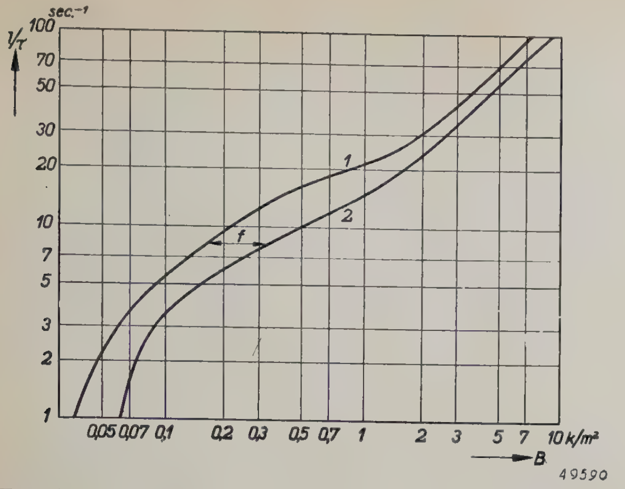

Fig. 6. The dependence of the velocity of observation $1/\tau$ on the brightness in the case of stationary objects:
1 for sodium and mercury light,
2 for incandescent lamp light.
For the same velocity of observation the brightness in case *2* must be a factor $f \approx 2$ times as large as in case *1*.

Fig. 6 holds for stationary objects [6], while *fig. 7* gives analogous curves for moving objects, those which flash past a slit (Weigel's observation [7]); since the velocity of motion was increased proportionally with $1/\tau$ we cannot expect to find such low values of τ here. In fig. 7 curve *1* represents the result with sodium light, curve *2* with incandescent electric lamps, curve *3* with mercury light. The fact that here the order differs from that in fig. 6 is not surprising, because quite different factors begin to play a part (after-image, extinction of the retinal image, etc.)

b) The time it takes to become conscious of the image and to recognize the object. This depends upon the clearness and the "striking" power of the image and especially whether it is anything common or uncommon.

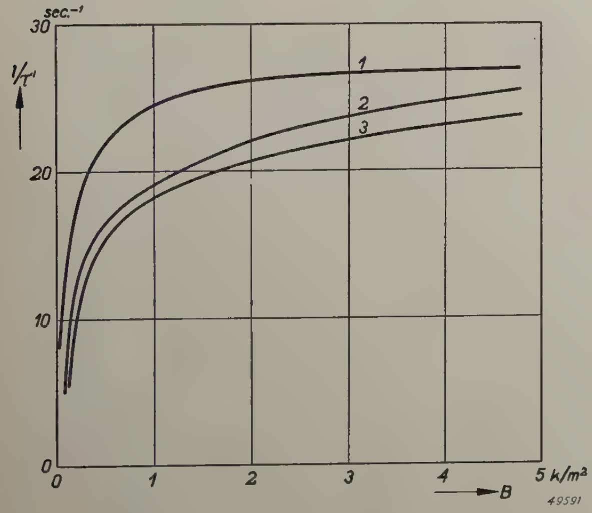

Fig. 7. The dependence of the velocity of observation $1/\tau$ on the brightness in the case of moving objects (according to Weigel).
1 for sodium light,
2 for incandescent lamp light,
3 for mercury light.

As to the order of magnitude of these periods of time, measurements of the velocity of reading teach us something. *Fig. 8* shows the number of letters of an easily legible text and good print that can be read per second without any particular strain [6] (curve *1* under sodium light and curve *2* under incandescent electric light). At very high levels of brightness a rate of 30 letters per second can be reached. What is actually measured is the variation of the sum of the times (a) and (b) according to the brightness. At very high levels of brightness the time (b) plays the main role, while at low levels (road lighting) both components are of importance.

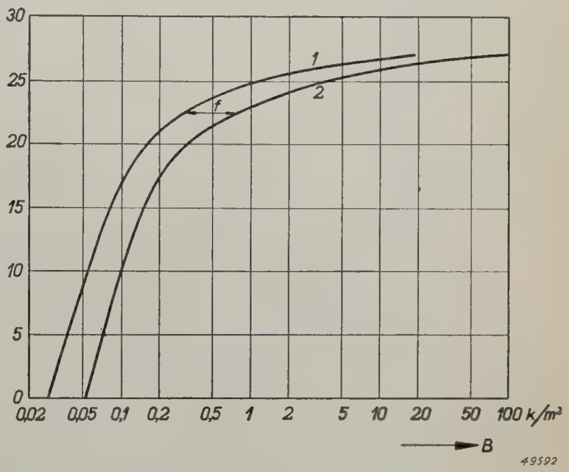

Fig. 8. The dependence of reading velocity on the brightness. As a measure of reading velocity the number of letters have been plotted which can be read per second under certain definite conditions:
1 for sodium light,
2 for incandescent lamp light.
Here too the factor f is about 2 (*cf.* fig. 6).

c) The time during which — consciously or unconsciously — the situation is weighed up: what must I do?

d) The time taken to set the reaction in motion. These last two periods of time have nothing to do with the eye and are influenced, among other things, by psychological factors (shock, concentration, distraction, difficulty of the problem, fatigue, etc).

Disturbing influences: glare

In general the disturbing effect of a given source of glare is all the greater according as the general level of brightness is lower and the visual task to be performed is more difficult. From this it follows that at the low brightnesses of road lighting and especially on fast traffic highways we must try to limit this disturbing influence to a minimum. Glare may be manifested in several ways:

a) *Glare depreciates the performance of the eye.*

The following are some examples of this form of disturbance (while the source of glare is present):

Example 1: At a distance of 2 metres to the side of an object 30 metres away there is a source of light radiating 810 candles in the direction of the observer and thus casting 0.9 lux on the eye. According to accepted standards such a source of light is considered "just troublesomely glaring" [8]. Because of this glare, with a normal brightness of the road surface the contrast sensitivity is found to have fallen by a factor 2.3. The seriousness of this is evident when it is considered that we should reach the same depreciation if the level of illumination were decreased by a factor of not less than 15! Moreover, it is assumed that the eye is kept fixed on the object and does not chance to look for a moment directly into the source of light. The reduction in visual acuity due to this degree of glare is much less, *viz.* about 15%. This is a general phenomenon: contrast sensitivity decreases much more due to glare than does visual acuity. Glare does not so much obscure the shape of the object but rather often causes it to fade entirely into the background.

Example 2: In order to give an idea of the extent to which glare may still occur with a modern road-lighting installation with well shielded light sources, we assume that the horizontally directed eye is struck by the light radiated at an angle of 70° to the vertical by a source of light (sodium lamp in an enamelled reflector) with a light intensity of 850 candles in that direction. The light falling on the eye in this case reduces the contrast sensitivity by about 10%, equivalent to the effect that would be obtained by reducing the level of brightness by a factor $1^1/_2$. This gives the degree of glare considered permissible with well-planned installations if the illumination is not to be too uneconomical. With many installations, however, the degree of glare encountered is many times greater.

Table I.

Smallest perceptible contrast		Ratio
With oncoming traffic	Without oncoming traffic	
$29^5\%$	$16^5\%$	1.8 : 1
44%	$12^5\%$	3.5 : 1
25%	$14^5\%$	1.7 : 1
$28^5\%$	10%	2.8 : 1

Example 3: *Table I* [2] gives an idea of the disturbing influence of oncoming traffic — even with dimmed headlights. For four different installations the smallest perceptible contrast was measured (with the above-described visibility meter) both with and without oncoming traffic. It appears that the glare from oncoming traffic causes the contrast sensitivity for small objects to fall on an average by a factor 2.

b) *After-effect, after-images*

After the source of glare has disappeared from the field of vision, its disturbing influence may still continue for some time (successive glare). We shall return to this later.

c) *Hindrance*

A third manifestation of the effect of glare is of a more psychological nature: the general feeling of hindrance, annoyance, and distraction of attention. These factors are difficult to measure and express in figures. We shall not, therefore, go more deeply into them here.

Disturbing influences: non-uniformity

The non-uniformity of the distribution of brightness on the road surface may also have a very disturbing effect that manifests itself in a depreciation of the performance of the eye [2]. This is illustrated by the figures in *table II*. For a given installation (sodium lighting, asphalt road surface) the smallest perceptible contrast was measured with the visibility meter at different states of wetness of the road surface: c_1 on the brightest spot of the road and c_2 on the darkest spot. It is found that with increasing wetness of the road surface the dark spots become darker and darker and the light spots brighter and brighter but also smaller. It is therefore understandable that c_2 increases, but from the table we see that c_1 also becomes larger with increasing wetness. It is thus clear that the unfavourable effect of the increasing non-uniformity of the distribution of brightness exceeds the favourable effect of the increase in the brightness itself:

Table II.

Condition of the road surface	Smallest perceptible contrast	
	c_1	c_2
Dry	17	31
Slightly damp	24	43
Damp	28	48
Wet	36	—

We may say that on an average with an installation with shielded sources of light and with a dry road surface the disturbing effect of the glare of the fixed light sources on the contrast sensitivity is the same as that due to a lowering of the level of brightness by a factor $1^1/_2$, while the disturbing effect of non-uniformity is equivalent to a lowering of the level of brightness by a factor 2. This agrees with fig. 1, where the measured points lie, on an average, a factor 3 to the right of the dotted-line curve.

Finally, non-uniformity may also cause various disturbances of a more psychological nature, which we shall not go into here. As examples we may mention certain light spots giving mistaken impressions of objects, whether or not we can see the road surface as a whole, distraction. fatigue, etc.

The part played by each component

In the foregoing the process of vision at low level of brightness has been resolved into a number of components. The question arises as to which components are of the greatest importance for visibility on the road. In general we may say that all the factors dealt with play an important part.

There is a lack of unanimity in literature as to whether the visual acuity and the closely related velocity of observation are also important factors. This depends very much on the speed at which one is driving on the road. As the speed increases it is necessary to be able to recognize objects at greater distances and thus within smaller angles of vision, so that the visual acuity begins to play a more and more important part. Since at high speeds delays in reaction of a fraction of a second may have fatal results, the speed of observation is also of much greater importance. The task of vision becomes more and more difficult as speed is increased, so that especially on fast-traffic highways every endeavour must be made to minimize the various disturbing elements.

It should also be noted that in the measurements with the visibility meter described above a number of the factors studied (contrast sensitivity, visual acuity, glare) are expressed in their correct relations.

Purkinje effect

In several respects it is of great significance for vision on the road that the eye possesses two different kinds of light-sensitive elements: the rods and the cones. These elements are distinguished not only by their shape, to which they owe their names, but also according to the following aspects:

a) By their different location on the retina. In the centre of the retina within a circle of some tenths of a millimeter there are only cones, while closer to the edges of the retina there are only rods, with a gradual transition between the two. The part of the retina containing cones is the part with which we see most sharply. It is for that reason that we stare directly at objects we wish to see sharply.

b) By their capacity of distinguishing colours. The cones can observe colour differences, the rods cannot.

c) By the difference in the range of brightness within which they function best. At high levels of brightness we see almost exclusively with the cones and at very low levels of brightness only with the rods. Between these extremes there is a transitory region where both elements make important contributions to vision. The following may serve as a general guide:
Level of brightness in daylight: exclusively cone vision.
Level of brightness artificial illumination indoors: usually exclusively cone vision.
Level of brightness road lighting; mixed vision, mainly with cones.
Level of brightness with full moon: mixed vision, mainly with rods.
Level of brightness with stars and no moon: exclusively rod vision.

d) By the difference in their eye-sensitivity curve. In *fig. 9* curve *A* is the eye-sensitivity curve for cone vision, *B* that for rod vision. The curve for mixed vision would lie intermediate. The cones are apparently most sensitive to yellowish green, the rods to bluish green. This difference in estimation of the brightness of colours has an important consequence. When a number of colours are given, all of which make an impression of equal brightness, and the amount of light

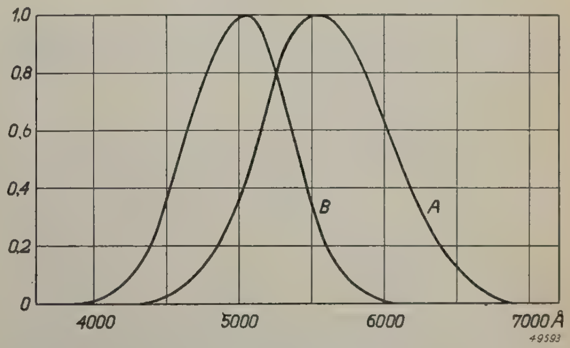

Fig. 9. Eye sensitivity (in relative units) as a function of the wavelength (in Å) for cone vision (*A*) and for rod vision (*B*).

radiated is then reduced by the same large factor for all colours, they are found no longer to give the impression of being "equally bright". The changed estimation of brightness for the different colours results in the bluish colours appearing to be brighter and the reddish colour less bright than the others (Purkinje effect).

If we were to reduce the brightness to such a low level as to get purely rod vision then the reddish kinds of light would ultimately become less efficient. In road-lighting practice, however, we work in the upper part of the transitory region; when a reddish light source is employed (for instance sodium light), it will therefore be "inferior in brightness" only for the darkest parts of the field of vision and not for the brighter parts. The result is that the dark objects appear extra black against the much lighter road surface (greater contrast).

Finally it may be noted that the distinction between rods and cones is also important in the study of the phenomena of glare, since we usually try to see as much as possible with the cones, while usually the glaring light mainly affects the rods.

Influence of colour on vision

In the following we will briefly review the influence of the colour of light on the various factors of vision, confining our considerations to the three most important kinds of artificial illumination: incandescent lamp light, mercury light and sodium light.

a) Influence on contrast sensitivity. Little difference between the three kinds of light.

b) The "striking" power of greater contrasts. In this respect sodium light offers important advantages (see above).

c) Visual acuity. In this respect mercury and sodium light are superior to incandescent lamp light; see fig. 5 (*1* mercury, *2* sodium, *4* incandescent lamps).

d) Velocity of observation of stationary objects. Here, too, mercury and sodium light are superior to incandescent lamp light; see fig. 6 (*1* mercury and sodium, *2* incandescent lamps).

e) Velocity of observation of moving objects. In this respect sodium light is superior and mercury light inferior to incandescent lamp light; see fig. 7 (*1* sodium, *2* incandescent lamps, *3* mercury).

It must be noted that on the road one is concerned more with case (*d*) than with case (*e*), since the movements on the road are for the most part towards or away from us; transversally there is little displacement of objects in our field of vision.

f) Glare; influence on visual acuity and contrast sensitivity. There is little difference here between the three kinds of light.

g) Glare; after-effect. *Fig. 10* gives measurements of the time of recovery of the visual acuity, *i.e.* the time elapsing after the disappearance of the source of glare until the visual acuity has again attained a certain value. This recovery time has been plotted in the vertical direction for the case where the glare was due to incandescent lamp light, and in the horizontal direction for an experimental case of glare due to sodium light under otherwise the same conditions. Each point recorded thus gives the recovery times t_1 and t_2 in analogous experiments for "white glare" and for "sodium glare". If there were no difference between the two kinds of light all the points would lie on the dotted line ($t_1 = t_2$). From the diagram it may be seen that taken on an average the recovery times t_1 for white light are a factor 1.8-2.0 longer than the corresponding times t_2 for sodium light [9].

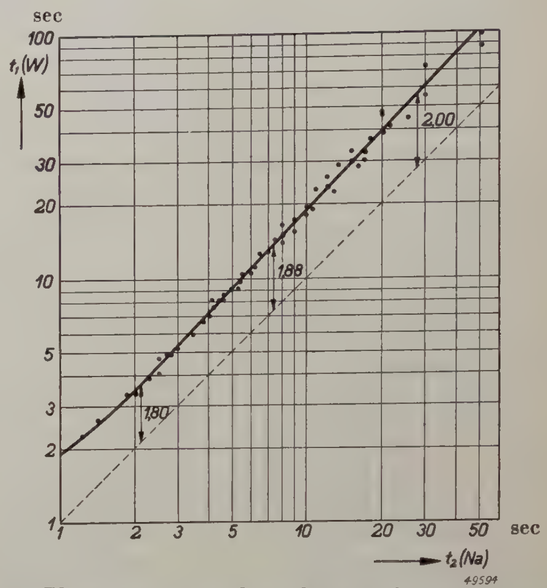

Fig. 10. The recovery time of visual acuity after glare is dependent on the colour of the light. With glare from white light (t_1) it is about twice as long as with glare from sodium light (t_2).

h) Glare; psychological effects. In general yellow light is found to be less disturbing than white light, though there are individual differences.

i) Experiments with the visibility meter.

Table III gives the average results obtained by measurements with the visibility meter with a large number of installations [2]. c_1 again indicates the just perceptible contrast (in %) for the brightest part of the road surface, c_2 for the darkest part.

It also gives the wattage used per kilometre and the lumens radiated by the lamps per metre of road length: the latter quantity was practically the same for the different kinds of light.

Table III.

Kind of light	State of road surface	c_1 (%)	c_2 (%)	$\frac{\text{kW}}{\text{km}}$	lm/m
Sodium	dry	17.2	31.2	3.3	200
Mercury	dry	26.0	35.4	6.4	220
Blended light	dry	21.4	35.3	10.8	230
Sodium	damp	24.1	44.3	3.4	210

It may be seen from the table that the results for the sodium installations exceed those for the mercury and blended light installations notwithstanding the much smaller power consumed. It also appears again that both c_1 and c_2 increase as the road surface becomes wet and thus the contrast sensitivity decreases both for the light and for the dark parts of the road surface.

Table III does not give any figures for incandescent lamp installations. Data have in fact been collected also for these installations — the results were by far less satisfactory than those given in table III — but a true comparison was impossible because most incandescent lamp installations already differ considerably from the sodium and mercury installations also in other respects.

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BOOK REVIEW

„**Kleuren en Kleurindrukken**"[1]), by P. J. Bouma, 320 pages, 113 illustrations and 15 tables, Philips Technical Library, Meulenhoff & Co. N.V., Amsterdam, 1946.

In this comprehensively written book (the reader is presumed to have a secondary school knowledge of mathematics and physics plus a certain amount of zeal!) the problem of colorimetry is approached from the angle of experimental physics and the theory of illumination. Other aspects of the many-sided field of the theory of colours which are connected with physiology and psychology are discussed only in so far as they are necessary for a proper understanding of the subject; also these discussions are kept on an experimental basis as far as possible. The aesthetic aspect has not been touched upon at all, neither have the physics and chemistry of dyes and pigments been dealt with.

Of the fourteen chapters, each divided into about ten sections, the first six are devoted to the theory of colour proper: the part played by the eye, the concept of brightness, the colour triangle and colour space. In contrast to the usual procedure and in accordance with Schrödinger, the author has restored colour space to a place of honour as basis for the theory of colour. The laws of Grassmann for the additive mixing of colour are dealt with at length in connection with colour space. Then follows an explanation of the international (C.I.E.) system of coordinates XYZ illustrated by a number of examples of calculation [2]).

The other chapters are devoted to special subjects. Chapter VII treats of several special cases such as the colours of black-body radiators, the boundary colours occurring upon refraction by a prism, the ideal remission curves, the so-called optimum colours (emission colours of maximum brightness) and the characteristic or most "colourful" colours (full colours).

Chapters VIII and IX give a survey of objective and subjective methods of colorimetry and of the instruments thereby employed.

In Chapter X the deviations from the normal sense of colour are described, dealing with the laws which these deviations obey, as well as their inheritability.

In Chapter XI the foremost personalities in the history of the science of colour are reviewed, with a short description of their contributions to this science: Newton, Goethe, Young, Grassmann, Maxwell, Helmholtz, A. König, Hering, Guild, Wright, Schrödinger, Ostwald.

In Chapters XII and XIII a number of questions are discussed which do not belong directly to the field of colorimetry, namely those cases where one is rather concerned with the concept of "colour sensation". Among these questions is the perception of colour differences and the study of the character of colour sensation, in particular the phenomenon of simultaneous contrast and the chromatic adaptation of the eye to coloured surroundings or to an illumination with more or less coloured light.

Finally Chapter XIV deals with several important fields of application, namely the theory of illumination, the applications in trade, industry and science (description of the colours of products and colour samples in trichromatic coordinates, employment of colour coordinates for the description of physical phenomena) and finally the problem of colour reproduction.

An appendix contains 15 tables, a bibliography with about 400 references to literature, a list of symbols employed and an index.

W. de Groot.

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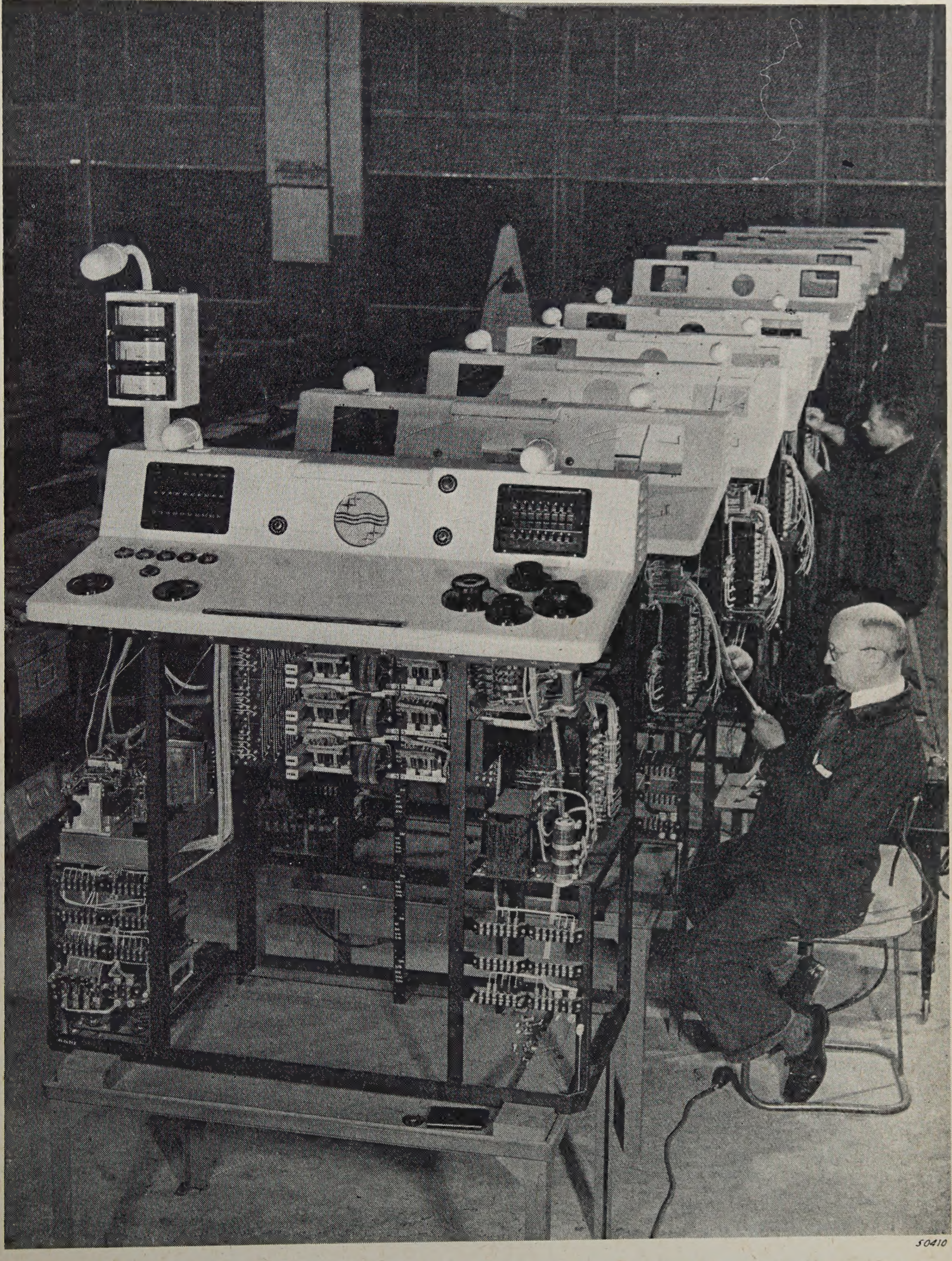
[1]) The title of the forthcoming English translation will be: "Physical Aspects of Colour, an introduction to the scientific study of Colour Stimuli and Colour Sensations".

[2]) The usefulness of the additive mixing laws is sometimes doubted. The number of cases in which one is concerned exclusively with these laws of mixing is indeed limited. In many cases problems arise which belong to the field of subtractive or multiplicative colour formation. The characterization of a colour by three numbers is then of little help and one is forced to have recourse to the spectral distribution function of the light source combined with the spectral transmission curve or spectral remission curve of a filter or of pigments. Moreover, in practice one is often concerned with the influence of the colour sensation, which is dependent on the surroundings. The possibility of fixing a colour by three coordinates, practically independently of the surroundings, furnishes, however, a means that can never be dispensed with.

ASSEMBLY OF SWITCHING DESKS FOR X-RAY DIAGNOSTIC APPARATUS



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An X-ray apparatus of the type shown here in course of construction (the Super D) can have eight X-ray tubes connected to it to be taken into use in turn. For each tube the desk is fitted with a so-called automatic unit providing for an optimum loading of the tube. Three such units, consisting of relays, resistors and contact plates, are seen underneath the middle part of the covering plate of the first desk, and five others can be placed underneath these. The tube to be used is selected by pressing in one of the eight push-button switches at the top of the desk on the right, thereby automatically switching over all the connections for the supply, the control mechanism, the safety devices and the signalling. This greatly simplifies operation, but it makes the apparatus complicated. The fitters have to make some thousand wire connections.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of the majority of these papers can be obtained on application to the Administration of the Research Laboratory, Kastanjelaan, Eindhoven, Netherlands. Those papers of which no reprints are available in sufficient number are marked with an asterisk.

1719/1721: C. J. Bouwkamp: On the dissection of rectangles into squares I, II, III (Proc. Kon Ned. Akad. Wetenschappen Amsterdam **49**, 1176-1188, 1946; **50**, 58-71, 72-78, 1947).

According to Brooks, Smith, Stone and Tutte, the semi-topological problem of the dissection of a rectangle into non-overlapping, unequal, squares is reduced to a physical problem: that of the current distribution in a planar electrical network consisting of equal resistances. The networks required for squarings of an order less than 15 are drawn. There are 2, 6, 22, 67, 214 perfectly squared rectangles of the order of 9, 10, 11, 12, 13 respectively. All these squarings are codified and classified. Special attention is paid to the construction of squared squares. At present it is not known whether a simple, perfect, squared square is possible.

Number 3 of volume 2, June, 1947, of *Philips Research Reports* contains the following papers:

R 42: W. Elenbaas: Influence of cooling conditions on high-pressure discharges.

R 43: H. C. Hamaker, H. Bruining and A. H. W. Aten Jr: On the activation of oxide-coated cathodes.

R 44: F. A. Kröger: Photoluminescence in the quaternary system $MgWO_4$ - $ZnWO_4$ - $MgMoO_4$ - $ZnMoO_4$.

R 45: F. A. Kröger: Luminescence of solid solutions of the system $CaMoO_4$ - $PbMoO_4$ and of some other systems.

R 46: R. Loosjes and H. J. Vink: The *i*, *V* characteristic of the coating of oxide cathodes during short-time thermionic emission.

R 47: J. D. Fast: The reaction between carbon and oxygen in liquid iron.

R 48: C. J. Bouwkamp: Calculation of the input impedance of a special antenna.

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